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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : B29B 13/08, B29C 31/06, 35/08	A1	(11) International Publication Number: WO 98/14314 (43) International Publication Date: 9 April 1998 (09.04.98)

(21) International Application Number: PCT/US97/17399

(22) International Filing Date: 26 September 1997 (26.09.97)

(30) Priority Data:
60/027,072 30 September 1996 (30.09.96) US

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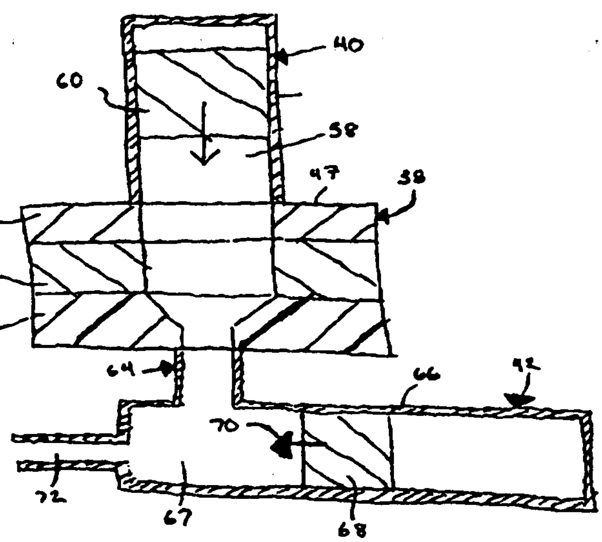
(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, US, UZ, VN, ARIPO patent (GH, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: MICROWAVE PROCESSING SYSTEM FOR POLYMERS



(57) Abstract

Polymer processing systems and methods which use microwave energy to achieve extremely rapid, efficient melting and/or softening of polymer materials. After rapid melting and/or softening is achieved, the molten polymer may then be pressurized for transport to an injection mold, an extrusion die, or the like, as desired. Microwave melting occurs so rapidly, that significant reductions in cycle time would be achieved by the present invention. Additionally, the use of microwave energy for melting is economically advantageous, because microwave energy sources are generally less costly and use energy more efficiently than conventional melting systems.

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MICROWAVE PROCESSING SYSTEM FOR POLYMERS

FIELD OF THE INVENTION

The present invention relates to a polymer processing apparatus and method for melting a polymer and then transporting the melted polymer to a point of use, such as an injection mold, an extrusion die, or the like. More specifically, the present invention relates to a polymer processing apparatus and method in which microwave energy is used to accomplish melting in one chamber and transport of the melted polymer to a point of use is accomplished from another independently pressurizable chamber.

BACKGROUND OF THE INVENTION

Articles formed from thermoplastic and thermosetting polymer resins are found everywhere and are used in an incredibly wide variety of applications. In spite of their widespread and divergent uses, most polymeric articles are formed using generally similar processing techniques. In a typical molding process, for example, a polymer resin is provided in a solid, pelletized form. The polymer resin pellets are initially melted or softened, and then the melted or softened material is brought into contact with an extrusion die or mold in which the polymer assumes the molded or extruded form of the intended article.

With respect to injection molding, cycle time refers collectively to the period of time it takes to first melt a given charge of polymer resin, then to transport the molten polymer into a mold, then to allow the melt to solidify in the mold to form the molded article, and finally to open the mold and remove the molded article. Faster cycle times are generally desired, because a higher output of molded articles can be produced per unit of time.

One factor affecting cycle time concerns the technique which is used to accomplish melting of the polymer material. With some melting approaches, the time required for melting is relatively long, thus adversely affecting cycle time.

Additionally, some melting approaches do not use energy efficiently, increasing the amount of energy required, and therefore the expense, for melting as compared to a process that is more energy efficient. Some melting approaches also require complex and/or expensive machinery, thus further increasing the costs associated with polymer processing. For example, many conventional injection molding and extrusion approaches rely primarily upon thermal conductivity of the material being heated in order to achieve melting. Because of limitations in the rate of heat transfer using such an approach, the flow rate of polymer material, and thus overall throughput of the polymer processing equipment, is also limited. Conventional heating also typically results in non-uniform heating throughout the bulk volume of the material being processed, and this non-uniformity typically must be overcome by constant motion, agitation, or stirring of the material been heated.

It would be desirable, therefore, to provide an approach which melts or softens polymer resins faster so that cycle time could be reduced. It would also be desirable if such an approach used energy more efficiently and required less complex, less expensive machinery so that the costs of polymer processing could be reduced.

Another factor affecting cycle time concerns the technique which is used to transport the melted polymer from the melting chamber to the injection mold or extrusion die. It would be desirable to provide an approach which accomplishes transport faster so that cycle time could be reduced. It would also be desirable if such an approach required less complex, less expensive machinery so that the costs of transporting the polymer melt could be reduced.

SUMMARY OF THE INVENTION

The present invention advantageously provides polymer processing systems and methods which use microwave energy to achieve extremely rapid, efficient melting and/or softening of polymer materials. An important advantage of microwave heating is the ability to heat polymer material volumetrically. That is, heat is transferred to the material throughout its cross-section by radiation rather than by thermal conduction. The rate of heat transfer is not limited by the thermal

conductivity of the material being heated, thus heat transfer occurs much faster. Microwave melting occurs so rapidly, that significant reductions in cycle time would be achieved by the present invention. Additionally, the use of microwave energy for melting is economically advantageous, because the system of the present invention uses energy more efficiently than conventional melting systems. Heating uniformity is also improved by microwave heating.

Further, preferred embodiments of the present invention include separate melting and metering chambers that can be pressurized independently of each other. This approach allows microwave melting to occur under a first, relatively low pressure, while molten polymer in the metering chamber can be pressurized to a second, relatively high pressure more suitable for extrusion, injection molding, or the like. This greatly simplifies the structure and construction of the apparatus.

In preferred embodiments of the invention suitable for injection molding operations, a piston or melt pump may be used to pressurize and convey the molten polymer from the metering chamber to the cavity of the injection mold. By using a piston or melt pump to accomplish such transport, rather than screws which are more conventionally used, cycle time and machinery costs are significantly reduced.

Preferred embodiments of the present invention involve conveying a continuous flow of polymer material through a conduit that not only serves as a passage for the polymer, but also serves as a single mode microwave cavity in which microwave energy is propagated along a path that substantially coincides with the path taken by the polymer being conveyed. Thus, the polymer flows through the conduit in the region where the electronic field, and hence heating efficiency, is at a maximum. Accordingly, this approach provides faster, more efficient, more flexible polymer melting capabilities. For example, both polar and nonpolar polymers may be quickly and continuously melted using the approach of the present invention. In contrast, many polymers, especially nonpolar polymers, are often difficult to melt with microwaves in a reasonable amount of time in a continuous process that involves conveying the polymer through a multimode

microwave cavity. As another advantage, residence time in the single mode microwave cavity of the present invention is also easily controlled merely by adjusting the length of the cavity. To increase residence time, for example, the length of the cavity can be increased without requiring any drop in material flow rate.

In many of the previously proposed schemes involving continuous flow of polymer through a conduit comprising a flux of microwave energy, the more centrally located flow has a tendency to overheat relative to portions of the flow closer to the conduit walls. Such nonuniform heating creates the danger that portions of the polymer will be burned, or otherwise degraded. Preferred embodiments of the invention rely upon a microwave transparent liner (e.g., a low loss ceramic such as quartz) to overcome both of these drawbacks. The liner helps to confine the polymer flow to conduit regions in which the microwave energy distribution is sufficiently uniform so that polymer burning or other degradation is easily avoided.

In one aspect, the present invention relates to a method of using microwave energy to process a composition comprising at least one meltable polymer. A charge comprising the composition is transported into a cavity in which the charge can be irradiated with microwave energy. While the charge is in the cavity, the charge is irradiated with microwave energy under conditions effective to melt the polymer. The melted polymer is then transported from the cavity to an independently pressurizable metering chamber. The melted polymer is then transported from the metering chamber to a point of use.

In another aspect, the present invention relates to an apparatus capable of using microwave energy to process a composition comprising at least one meltable polymer. The apparatus includes an electrically conductive housing defining a microwave processing cavity. A microwave energy source is operationally coupled to the cavity such that, while the charge is in the cavity, the charge can be irradiated with microwave energy under conditions effective to melt the polymer. A chamber is in fluid communication with the cavity such that the melted polymer can be transported from the cavity to the chamber. A transport

mechanism is operationally coupled to the chamber in a manner such that melted polymer in the chamber can be transported to a point of use.

In another aspect, the present invention relates to a process of using microwave energy to process a composition comprising at least one meltable polymer. A rotatable member is provided comprising a first cavity for holding a charge comprising a polymer resin. The rotatable member is rotated to a first position such that the cavity is in communication with a supply comprising the polymer. A charge comprising the polymer from the supply is delivered to the cavity. After delivering the charge to the cavity, the charge is irradiated with microwave energy under conditions effective to melt substantially all of the polymer, wherein said irradiating step occurs after the rotatable member is rotated away from the first position. After melting the polymer, at least a portion of the melted polymer is transported to a metering chamber. The melted polymer is transported from the metering chamber to a point of use.

In another aspect, the present invention relates to a process of using microwave energy to process a composition comprising at least one meltable polymer. A rotatable member is provided, wherein the rotatable member comprises first, second, and third cavities, wherein rotation of the rotatable member causes each of the cavities to move sequentially through successive delivery, irradiating, and transport positions of a processing cycle, wherein such cycle is successively repeated by each cavity as the rotatable member rotates, and wherein the one cavity in the delivery position is capable of receiving a charge comprising the polymer, the one cavity in the irradiating position holds a charge of the composition during irradiation, and the one cavity in the transport position holds a charge comprising a substantially melted polymer resin. A charge comprising a substantially unmelted polymer resin is delivered to the cavity in the delivery position. The charge held in the cavity disposed in the irradiating position is irradiated with an amount of microwave energy sufficient to melt substantially all of the polymer resin of said charge. At least a portion of the charge held in the cavity in the transport position is transported to a metering chamber such that said cavity is capable of receiving an additional charge comprising a polymer resin. The charge from the metering

chamber is injected into a mold comprising an internal volume having a shape corresponding to the article to be molded. The rotatable member is rotated such that each of the cavities is advanced sequentially to the next corresponding position of the processing cycle. Steps (b) through (f) are repeated a plurality of times.

In another aspect, the invention relates to an apparatus for processing a composition comprising at least one meltable polymer. The apparatus includes a rotatable member comprising a cavity for holding a charge of the composition. A microwave energy source is operationally coupled to the cavity such that the charge in the cavity can be irradiated with microwave energy under conditions effective to melt the polymer. A metering chamber is capable of being in fluid communication with the cavity so that the charge can be transported from the cavity to the metering chamber. A first transport mechanism is operationally positioned in the apparatus such that the first transport mechanism is capable of transporting the charge from the metering chamber to a point of use.

BRIEF DESCRIPTION OF THE DRAWINGS

The above-mentioned and other features and advantages of this invention, and the manner of attaining them, will become more apparent and the invention will be better understood by reference to the following description of an embodiment of the invention taken in conjunction with the accompanying drawings, wherein:

Fig. 1 is a schematic representation of a system for melting polymers according to the present invention;

Fig. 2 is a perspective schematic view of a polymer processing apparatus according to one embodiment of the present invention;

Fig. 3 is a side sectional view of the main processing unit used in the embodiment of Fig. 2 in which a cavity is shown in the irradiating position;

Fig. 4 is a side sectional view of the hopper and main processing unit of the embodiment of Fig. 2 in which a cavity is shown in the delivery position;

Fig. 5 is a side sectional view of the transfer cylinder, injection mechanism, and main processing unit of the embodiment of Fig. 2 in which a cavity is shown in the transport position;

Fig. 6 is a side sectional view of a polymer processing apparatus according to an alternative embodiment of the present invention; and

Fig. 7 is a side sectional view of a polymer processing apparatus according to an alternative embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The various aspects of the present invention will now be described with reference to the particular embodiments of the present invention shown in Figs. 1 through 7. However, the embodiments disclosed below are not intended to be exhaustive or to limit the invention to the precise forms disclosed in the following detailed description.

Fig. 1 is a schematic representation of a polymer processing system 10 incorporating the principles of the present invention. System 10 is adapted to melt a feed 12 comprising at least one polymer resin, and then deliver the molten polymer to a point of use 14, which may be the cavity of an injection mold, an extrusion die, or the like. Advantageously, a wide variety of thermosetting and thermoplastic polymer resins known to be suitable for molding or extrusion can be processed using system 10, although the use of thermoplastic materials is commonly preferred for injection molding applications. Examples of such thermoplastic and/or thermosetting materials suitable in the practice of the present invention include polyethylene; polypropylene; polyether; polyester; a copolymer comprising butadiene and styrene; a copolymer comprising acrylonitrile, butadiene, and styrene (ABS); polyurethane; vinyl resin such as polyvinyl chloride; polyamide (such as the various polyamide resins referred to as "nylons"); epoxy resin, phenolic resin; polyimides; polyamideimides; vulcanized rubbers (synthetic and natural); fluorinated polyolefins such as polytetrafluoroethylene and polyvinyldene fluoride; acrylic resin such as polymethylmethacrylate; polysulfones, acetal resin; bismaleimide resin; cellulosic resin; ketone based resin; liquid crystal polymer;

melamine-formaldehyde resin; polycarbonate; polyetherimide; other polyalkylene resin such as polymethylpentene; nitrile resin; polyphthalamide; silicone resin; urea resin; sulfone-based resin; combinations thereof, and the like. For a description of such resins, see, e.g., Plastics Handbook, edited by Modern Plastics, McGraw-Hill, Inc., 1994.

Generally, relatively polar polymers such as polyvinyl chloride, polyamide, polyurethane, epoxy, polyimide, vulcanized rubber, ABS, and the like, tend to absorb enough microwave energy by themselves so that microwave melting can be accomplished without the use of microwave energy absorbing additives. On the other hand, relatively nonpolar polymers such as polyolefins, polyester, polystyrene, high impact polystyrene, polytetrafluoroethylene, allyl resin, styrenic resin, and the like, typically do not by themselves absorb significant amounts of microwave energy. As a result, irradiating such materials with just microwave energy may not be effective to achieve the desired melting or softening of such nonpolar materials. Accordingly, it is preferred that any such nonpolar polymer resin, or resins, are combined with an effective amount of a microwave absorbing additive, or "sensitizer" as such materials are referred to in the art. Advantageously, such an additive will absorb microwave energy, which heats the additive. Such heat is then thermally transferred to the nonpolar polymer resin, causing the polymer resin to melt or soften as desired. When the additive is homogeneously distributed throughout the bulk volume of the polymer, this heat transfer is extremely rapid.

The microwave absorbing additive generally may be any solid or liquid polar compound or combination of such compounds capable of absorbing and being heated by microwave energy and then thermally transferring the resultant heat energy to the polymer material to be processed. Such additives can be organic or inorganic. Organic polar compounds may be monomeric, oligomeric, or polymeric. Examples of representative classes of materials suitable for use as a microwave absorbing additive include any material known to function as an antistatic agent, carbon fibers, metal powder, color retardants of the type used in paint compositions, ultraviolet light absorbing materials commonly used in paint

compositions, metal hydroxides such as $Mg(OH)_2$, other inorganic salts such as $CaSO_4 \bullet H_2O$ and $MgSO_4 \bullet H_2O$; fatty acids; fatty acid esters; water; glyceryl esters; alcohols; amides; amines; hydroxylated amines such as ethanolamine; alkylene glycols; quaternary ammonium salts, low molecular weight polar polymers and oligomers having a weight average molecular weight in the range from 200 to 8000 such as polyethylene glycol and polyvinyl alcohol, combinations of these and the like. For food grade products, FDA-approved additives such as $Mg(OH)_2$, are particularly preferred.

Choosing an appropriate amount of the microwave absorbing additive will depend upon a variety of factors such as the polymer resin being processed, the identity of the additive being used, the microwave frequency, the power output level of the microwave energy source, and the like. In selecting an appropriate amount of the microwave absorbing additive, enough of the additive should be combined with the polymer resin such that substantially complete melting, or the desired degree of softening, of the resin is achieved. If too little of the microwave absorbing additive were to be used, an insufficient degree of melting or softening may occur. On the other hand, if too much is used, the physical properties of the resultant polymeric article may be impaired. Additionally, if too much of the additive were to be used, too much heat may be generated which might degrade or burn the polymer. Generally, using 0.01 to about 20, preferably 0.01 to about 5, parts by weight of the additive per 100 parts by weight of the polymer resin would be suitable in the practice of the present invention.

The microwave absorbing additive can be incorporated into feed 12 in any desired, convenient manner. For example, if the additive is a liquid, then pellets of the polymer and liquid can be "pre-tumbled" together in order to coat the pellets with the liquid. Alternatively, if the additive is a solid, then the additive and the polymer may be compounded together to achieve a homogeneous admixture of the ingredients. The use of microwave energy absorbing additives to allow nonpolar polymer resins to be heated with microwave energy has been described in

the art. See, e.g., U.S. Pat. Nos. 4,288,399; 4,360,607; 4,400,483; 4,840,758; and 5,446,270.

System 10 generally comprises a first stage of operation represented by microwave cavity 16 in which feed 12 is melted using microwave energy, and a second stage of operation 22 in which the molten feed is pressurized for transport to point of use 14. This "multistage" approach allows microwave melting to occur at relatively low pressure, greatly simplifying the construction of microwave cavity 16 relative to a single-stage system in which microwave melting and pressurization for transport occur in the microwave cavity.

Microwave cavity 16 is generally defined by walls formed from electrically conductive material(s) that electrically shield the cavity, thereby substantially preventing microwaves from escaping from microwave cavity 16. Representative examples of such materials are well-known in the art and include corrosion-resistant metals, metal alloys, intermetallic compositions, combinations of these, and the like. Preferred examples of such materials include aluminum, stainless steel, copper, die-cast zinc, combinations of these, and the like.

Microwave cavity 16 can be either a single mode microwave cavity or a multi-mode microwave cavity, as desired. The term "mode" refers to the specific electromagnetic field pattern that develops inside a microwave cavity. The mode pattern is governed primarily by the internal geometry of the cavity and the wavelength of the electromagnetic energy which propagates within the cavity. A multi-mode cavity generally refers to a microwave cavity that is relatively large compared to the wavelength of microwave energy, such as, for example, a household microwave oven. A multi-mode microwave cavity generally contains multiple mode patterns which tend to be somewhat random. The electric field strength throughout a multi-mode cavity, therefore, is typically random and difficult to control. When materials are heated in a multi-mode cavity, heating uniformity can be improved by constant motion, agitation, or stirring of the material.

In contrast, a single mode microwave cavity refers to a smaller cavity that is capable of supporting only a single well-defined mode pattern which tends to be very regular and predictable. When materials are heated in a single-mode

cavity, good heating uniformity results without requiring constant motion, agitation, or stirring of the material being processed. As compared to a multi-mode cavity, heating is significantly more uniform and easier to control in a single mode cavity. In the practice of the present invention, a single mode microwave cavity is generally more suitable for use in a continuous process (see for example the embodiments of the present invention described below in connection with Figs. 6 and 7), and a multi-mold microwave cavity is generally more suitable for use in a batch process (see for example the embodiment of the present invention described below in connection with Figs. 2-5).

Microwave cavity 16 can be provided with any suitable shape and dimensions. The precise configuration of microwave cavity 16 will depend upon a variety of factors including, for example, the frequency of the microwave energy, the residence time required to accomplish melting, whether cavity 16 is intended for multimode or single mode operation, whether cavity 16 is intended for batch and continuous processing, and the like. Preferred microwave cavities 16 of the invention, nonetheless, are provided with a cylindrical shape, because cylindrically-shaped cavities can be relatively easily provided with dimensions effective to resonate at the frequency of the microwave energy supplied by microwave source 18 so as to promote even energy distribution in microwave cavity 16. Depending upon the mode of operation, microwaves can be propagated along the longitudinal axis of such cylindrically-shaped cavities, generally perpendicular to such axis, or at an angle to such axis, as desired.

In particularly preferred embodiments of the present invention, microwave cavity 16 is cylindrical in shape and is configured to provide a single mode pattern which places the electric field parallel to the axis of the cavity. The material being heated is then conveyed through the cavity in line with the axis and electric field in order to achieve the maximum heating efficiency. Even more preferably, in order to further optimize heating performance, a cylindrically-shaped, single mode microwave cavity of the present invention has the so-called TM_{020} mode configuration in which a peak electric field exists at the center axis of the

cavity with another peak forming an annulus about the center axis. The electric fields in both peaks thus are parallel to the center axis of the cylindrical cavity.

As an option, at least a portion and preferably substantially all of the interior surfaces of the electrically conductive walls defining microwave cavity 16 are sufficiently reflective so that at least a portion of the radiant heat energy generated during polymer melting is reflected back into microwave cavity 16 in order to promote more effective melting of the polymer resin(s) being processed. The interior surfaces of the cavity walls are preferably as reflective as practical circumstances allow. Although a surface cannot be too reflective from a technical perspective, there is a level of reflectivity beyond which the incremental improvement in performance offered by additional improvement in reflectivity characteristics may not justify the extra cost of attaining such improvement.

Advantageously, using the combination of both microwave energy and reflected radiant energy provides much better melting performance than using microwave energy alone, particularly when nonpolar polymers are being processed. For example, some non-polar polymers may not melt upon irradiation with just microwave energy alone unless relatively large quantities of a microwave energy absorbing additive is blended with, or otherwise incorporated into, the non-polar polymer. However, when the interior surfaces of the microwave cavity walls are highly reflective such that both microwave energy and reflected radiant energy are used to accomplish melting, many kinds of non-polar polymers can be melted with lesser quantities of such additives. In some instances, the amount of reflected radiant energy is sufficiently great so that the presence of microwave energy absorbing additives can be avoided altogether.

Any technique known in the art can be used to provide the interior surfaces of the microwave cavity walls with the desired level of reflective characteristics. As one approach, for example, the interior surfaces of electrically conductive cavity walls formed from aluminum, stainless-steel, copper, or the like, can be polished in order to enhance the reflective characteristics of such surfaces. As an alternative approach, instead of polishing the interior surfaces of the walls,

the interior surfaces can be coated with an intrinsically reflective material such as gold, silver, nickel, or the like.

Determining whether a surface treatment is desired for enhanced reflectivity will depend, in part, upon the type of material from which microwave cavity 16 is formed. Materials intrinsically characterized by low wall losses within the intended operating regime may not require any kind of surface treatment to enhance reflectivity. On the other hand, a surface treatment may be more desirable for materials having relatively high wall losses in the intended operating regime. For example, a microwave cavity formed from aluminum provides excellent performance in high Q applications and may not require any kind of surface treatment. However, stainless steel, which is stronger than aluminum and better for cavities subjected to high internal pressures, nonetheless contributes to higher wall losses than aluminum. Therefore, a surface treatment involving polishing and/or applying a finish of nickel, gold, or platinum may be desirable for stainless steel cavities.

In the practice of the present invention, the reflective characteristics of the interior surfaces of microwave cavity 16 can be quantitatively defined in terms of emissivity. Emissivity refers to the ratio of the radiation emitted by a surface as compared to the radiation emitted by a black body at the same temperature. Materials with lower emissivity are more reflective than materials with higher resistivity. For purposes of the present invention, the interior surfaces of microwave cavity 16 preferably have an emissivity of less than 0.1, more preferably 0.05 or less.

Microwave energy for melting is supplied to microwave cavity 16 by microwave source 18 through waveguide 20. In the practice of the present invention, microwave energy refers to electromagnetic radiation characterized by a wavelength greater than radio waves but shorter than infrared radiation. Preferred microwaves are characterized by a wavelength of about 1 mm (about 300 GHz) to about 50 cm (about 0.6 GHz). More preferred microwaves have a wavelength such that the frequency of the microwaves is in the range from about 0.9 GHz to about 5 GHz, preferably about 0.915 GHz or about 2.45 GHz.

The most common factors to be considered when selecting the most practical microwave source 20 are operating frequency, power requirement, output waveform and cost. In most case size and weight are of secondary importance, but these factors should not be overlooked if space is limited or ease of maintenance is critical. With respect to operating frequency, microwave source 18 may be tunable so that microwave source 18 is capable of generating a range of microwave frequencies. Alternatively, microwave source 18 may be of a "universal" type that generates microwaves characterized by only a single frequency. Use of a "universal" type microwave source 18 is preferred because microwave sources that generate either 2.45 GHz or 0.915 GHz microwaves, respectively, are widely available at economic prices from a number of commercial sources. Microwave sources operating at 2.45 GHz are more preferred.

Microwave source 20 should have an appropriate power output such that microwave energy source 20 is capable of radiating microwave energy at a power level sufficient to achieve melting or softening, as desired, of the polymer resin(s) being processed. On the other hand, using too much power could degrade or burn the polymer resin. Proper selection of a suitable power output for the microwave energy source would depend upon a variety of factors including the particular microwave energy source 20 being used, the polymer resin being processed, and the like. Generally, however, an available power output level in the range from about 0.5 kW to about 500 kW would be suitable in the practice of the present invention. In order to provide the flexibility to process a wide variety of polymers having different melting characteristics, it is preferred that the power output level of microwave energy source 18 be controllably variable over such a wide range. As a specific example, 2.45 GHz microwave sources are most commonly available with power output ranging from 500 Watts up to 6 kW, while a few manufacturers offer units with output up to 30 kW. Units operating at 6 kW are preferred.

The output waveform from microwave source 20 is directly related to its output spectrum and is an important factor when delivering microwave power to a high Q load. Less expensive generators utilizing power supplies commonly found in household microwave ovens have a pulsed waveform

where pulse rate is equal to the power line frequency (60 Hz in the US) and an output spectral bandwidth of approximately 5 MHz. In contrast, high performance generators utilizing switch mode power supplies have extremely low ripple, or CW, waveforms and typical output spectral bandwidths of approximately 250 kHz. A useful rule of thumb is to use a microwave source having a spectral bandwidth no more than half the coupling bandwidth of the load being heated. For example, polyethylene, being characterized by a Q factor of 4000, has a coupling bandwidth (Δf) of 613 kHz when operating at 2.45 GHz. For good operational stability this requires a microwave source having an output spectral bandwidth of no more than 300 kHz. The use of any generator with a broader spectral output will result in reduced coupling efficiency and/or operational instability. Therefore, low ripple generators, which have such capabilities, are preferred.

Waveguide 20 is typically a pipelike structure that may have any suitable cross-section for carrying microwaves from microwave source 18 to microwave cavity 16. Preferred waveguides 20 have either a square, rectangular, or circular cross-section. Like the walls used to define microwave cavity 16, waveguide 20 is generally formed from an electrically conductive material such as a corrosion-resistant metal, a metal alloy, an intermetallic composition, combinations of these, and the like. Preferred waveguides comprise aluminum, stainless steel, and/or copper.

Waveguide 20 may be flexible if desirable or necessary to allow for tolerance build-ups between the respective mounting positions of the applicator and microwave generator. Flexible waveguide 20 can also be used where movement between mounting positions is required. However, flexible waveguide 20 could be subject to fatigue failure due to repeated working of its metallic structure. Caution should be exercised during the design phase to limit the amount of flexure sufficiently to prevent any portion of the metallic structure from reaching its yield point while flexing.

Almost all microwave power delivery systems require a device which is used to match the impedance of the load to that of the waveguide and thus the microwave generator. Without this the amount of microwave power coupled to

the load may be partially reduced. The most common form of this device is a waveguide stub tuner, but other types of devices such as irises are also used. Waveguide tuners are popular for their convenience in adjusting the match while microwave power is being delivered.

Tuners are available for either manual or automatic operation. Manual tuners are adjusted by turning one or more stubs, or threaded rods, into the waveguide while the operator observes a power meter which monitors the amount of microwave power reflected from the load. Tuning is accomplished when reflected power is minimized. Automatic tuners operate essentially the same way, except that the stubs are driven by motors and sophisticated electronics are used to monitor reflected power and adjust the stubs accordingly.

Selecting between manual and automatic tuners depends more on the requirements of the process than on the cost of the device. When power is being delivered to a high Q load, the tuner often requires adjustment if the power output from the generator changes, such as is often required for regulating processes. As the generator changes output power, its center frequency also changes by as much as 30 MHz from zero to full output (this is a characteristic of all microwave generators which utilize magnetrons). When the Q of the load is 4000 and coupling bandwidth only 600 kHz, a small change in power output can result in complete loss of coupling to the load. Similarly, a dynamic process during which the characteristic impedance is constantly changing or changes gradually over time requires constant tuner adjustments in order to maintain coupling throughout the process. Under these conditions, automatic tuners are often preferred over manual tuners for their convenience and ease of use.

Most commercially available tuners, whether manual or automatic, have three or four stubs for more versatile impedance matching. In certain cases it may be possible to accomplish all of the tuning requirements using only a single stub. If this is the case, a significant amount of cost can be reduced for this components requirement. However, the ability to use only a single stub can only be determined experimentally on the actual configuration of equipment for which it is desired.

Another component typically used by most industrial microwave heating systems is a waveguide isolator which is used to protect the magnetron (the device which actually produces the microwave energy) from reflected power. The isolator includes a waveguide circulator, which directs the reflected power away from the magnetron and a dummy load which absorbs and dissipates the reflected power. Often these two elements exist as separate components which work together, but they are also available from some manufacturers incorporated together as a single component.

A means to measure reflected power for tuning purposes is also desirable. Waveguide power couplers and meters are available as separate components which can be incorporated into the heating system, but they are also available as a feature of the isolator.

Other miscellaneous waveguide components may also be desirable depending on the configuration of the equipment onto which they are to be installed. These components typically include short sections of rigid waveguide with one or more elbows to direct the microwave energy around corners. Almost any configuration is possible.

Figs. 2-5 show a specific configuration of one preferred embodiment of a polymer processing apparatus 30 of the present invention. Apparatus 30 is provided with four main components including hopper 36, main processing unit 38, transfer cylinder 40, and injection mechanism 42. Although the apparatus 30 of Figs. 2-5 is shown as having only one each of these four components, one or more additional hoppers, main processing units, transfer cylinders, and/or injection mechanisms may also be provided in order to increase the output capacity of apparatus 20.

Main processing unit 38 is cylindrically shaped and is used to melt a charge comprising a polymer resin received from raw material supply 32 provided in hopper 36. Main processing unit 38 includes a top housing section 44, center plate section 46, and bottom housing section 48. Center plate section 46 is rotatable about axis of rotation 49 and thus provides main processing unit 38 with a rotatable member to facilitate delivery, melting, and transport of polymer charges to

be processed. In the preferred embodiment shown in the Figures, top and bottom housing sections 44 and 48 are fixed and do not rotate. Center plate section 46 includes a top axial face 51 disposed proximal to top housing section 44 and a bottom axial face 53 disposed proximal to bottom housing section 48. The top axial face 51 of center plate section 46 is provided with first, second, and third cavities 50, 52, and 54 which are adapted to hold respective charges of polymer resin to be processed.

Hopper 36 and transfer cylinder 40 are disposed on the top surface 47 of top housing section 44 approximately 120 degrees apart. Intermediately between hopper 36 and transfer cylinder 40, main processing unit 38 is provided with a microwave energy source. As shown in Fig. 1, at least a portion 21 of the microwave energy source is disposed in top housing section 24. The microwave energy source is capable of directing microwave energy at the contents of one of cavities 50, 52, or 54 when center plate section 46 is rotated to a position such that one of such cavities is disposed below the microwave energy source portion 41.

Although apparatus 30 is configured with the microwave energy source portion 41 being disposed in top housing section 44, other configurations could also be used. For example, rather than being disposed in top housing section 44, the microwave energy portion 41 could be disposed in an analogous position in bottom housing section 48. Alternatively, portions of the microwave energy source could be disposed in both the top and bottom housing sections 44 and 48 in a manner such that the two portions would cooperate to irradiate the contents of an interposed cavity with microwave energy. In still other embodiments, at least a portion of the microwave energy source could be disposed in center plate section peripherally around each of the cavities. As still another alternative, the microwave source could be completely external to apparatus 30, but operationally coupled to apparatus 30 by a suitable waveguide.

It can be appreciated, therefore, that rotation of center plate section 46 about axis of rotation 49 causes each of cavities 50, 52, and 54 to move sequentially through successive delivery, irradiating, and transport positions of a polymer processing cycle. This processing cycle is successively repeated by each

cavity 50, 52, and 54 as center plate section 46 rotates. As seen best in Fig. 4, the delivery position of the cycle corresponds to the position of a cavity 50 which is rotated to a position at which a charge from supply 32 can be delivered to the cavity 50. In the embodiment shown in Fig. 4, cavity 50 disposed directly below hopper 34 is in the delivery position. To facilitate delivery, top housing section 44 is provided with a through aperture 55 allowing communication between hopper 36 and the cavity 50 in the delivery position. Preferably, controlling means (not shown) is provided so that the amount and timing of charges delivered from supply 32 through the aperture 55 can be controlled by the operator. The kind of controlling means used is not critical, and any such means could be used in accordance with conventional practices.

As seen best in Fig. 3, the irradiation position corresponds to the position of a cavity 52 which is rotated to a position at which the contents of the cavity 52 can be irradiated with microwave energy by the microwave energy source portion 41. In the embodiment shown in Fig. 3, cavity 52 disposed directly below microwave energy source portion 41 is in the delivery position. When cavity 52 holding a charge comprising a polymer resin is in this position, irradiation of the charge with microwave energy causes the polymer resin to melt. Advantageously, such melting occurs extremely rapidly and much more quickly than could be achieved using conventional melting techniques.

As seen best in Fig. 5, the transport position corresponds to the position of a cavity 54 which is rotated to a position at which the action of transfer cylinder 40 can be used to transfer the contents of the cavity 54 to the injection mechanism 42. Transfer cylinder 40 is provided with housing 56 defining a cylinder bore 58. A piston 60 capable of reciprocating movement upward and downward in cylinder bore 58 is also provided. Top housing section 44 is provided with through aperture 62 coupling the internal volume of cylinder bore 58 to cavity 54 in the transport position. The cavity 54 in the transport position is fluidly coupled to the interior of injection mechanism 42 by passageway 64. Passageway is formed from through aperture 63 and conduct section 65. As a result, downward

movement of piston 60 forces a melted charge from the transport cavity through passageway 64 and into the injection mechanism 42.

Injection mechanism 42 includes housing 66 enclosing a metering chamber 67 for holding a metered amount of the molten charge. Injection mechanism 42 is further provided with a piston 68 which is capable of reciprocating movement inside housing 66 in directions along the longitudinal axis of injection mechanism 42. Piston 68 is disposed so that movement of the piston in the direction of arrow 70 forces a molten polymer 34 through output passage 72. From output passage 72, the molten polymer can be directed to a point of use such as an extrusion die (not shown) or the internal volume of a mold (not shown), wherein the mold volume has a shape corresponding to the shape of the article to be formed.

According to a preferred mode of operation, supply 32 comprising polymer resin to be processed is provided in hopper 36. During polymer processing, the center plate section 46 is rotated until each of cavities 50, 52, and 54 is at a respective one of the delivery, irradiating, and transport positions. Typically during steady state operations, the cavity at the delivery position is capable of receiving a charge comprising the polymer resin, the cavity at the irradiation position holds a charge comprising solid polymer resin which is ready to be melted, and the cavity at the transport position holds a charge of substantially melted polymer resin ready to be transported to the injection mechanism 42. Accordingly, while the center plate section 46 is at such a position, a charge comprising a substantially unmelted polymer resin is delivered to the cavity 50 in the delivery position; the charge held in the cavity 52 disposed in the irradiating position is irradiated with an amount of microwave energy sufficient to melt substantially all of the polymer resin of said charge; and at least a portion of the charge 54 held in the cavity in the transport position is transported to metering chamber 67 such that the cavity 54 is capable of receiving a successive charge comprising a polymer resin in the next step of the processing cycle. The charge in the metering chamber 62 may then be injected into a mold (not shown) comprising

an internal volume having a shape corresponding to the article to be molded, or extruded through an extrusion die, as desired.

After the charge at the transport position is transferred to the metering chamber 67, the center plate section 46 rotates until the cavities 50, 52 and 54 are advanced to the next position of the processing cycle, and the delivery, irradiation, transport, and injection steps are then repeated. The process cycle can be repeated as many times as desired.

Fig. 6 shows an alternative embodiment of a polymer processing apparatus 100 of the present invention. Apparatus 100 is adapted for continuous processing of a supply 102 comprising a polymer material to be melted and subsequently delivered to a point of use (not shown). Apparatus 100 includes melting unit 104 and transport unit 106 operationally coupled to melting unit 104 by conduit 106. Melting is accomplished in melting unit 104, and the molten polymer is then pressurized in transport mechanism 106 for transport to the point of use.

Melting unit 104 includes electrically conductive, cylindrical housing 112 formed from sidewall 114, bottom 116, top 118, and interior partition 120. Interior partition 120 divides housing 112 into a feed zone 122 and a melting zone 124. The center region of interior partition 120 is fitted with perforated plate 126 that comprises a plurality of apertures permitting feed 102 to pass from feed zone 122 into melting zone 124. Preferably, interior partition 120 and perforated plate 126 are formed from an electrically conductive material to provide electric shielding at the top of melting zone 124. As an option, a cooling jacket (not shown) may be provided on the exterior of housing 112 in order to carry away excess heat generated during melting operations.

Feed zone 122 includes rotatable feed screw 128 operationally supported in housing 112 and bushing member 130, which defines the inner diameter of the feeding section. Bushing member 130 preferably is formed from hardened steel. Bushing member 130 is fixedly attached to housing 112 by any suitable technique including welding, riveting, bonding with an adhesive, press fitting, and the like. Charge 132 of supply 102 provided in hopper 134 is gravity

fed into helical chamber 136 defined by interior surface 131 of bushing member 130, feed member threads 138, and center member 140. Rotation of feed screw 128 motivates charge 132 through perforated plate 126 and into melting zone 124. The feed rate can be controlled easily by adjusting the rotational speed of feed screw 128. Generally, faster rotation of feed screw 128 provides higher feed rates. Preferably, feed screw 128 is rotated at a rate so that a substantially continuous, steady state flow of polymer material through melting unit 104 can be maintained.

Melting zone 124 includes cylindrically shaped, single mode chamber 140 operationally coupled to microwave source 137 by waveguide 139. Although only one microwave source 137 and waveguide 139 is shown, one or more microwave sources in combination with one or more waveguides coupled to chamber 140 at one or more positions could also be used. In the preferred embodiment shown, chamber 140 not only functions as a passage for polymer material to be conveyed through melting unit 104, but cavity 140 also functions as a single mode microwave cavity. Thus, both microwaves and the polymer material are both conveyed along a path substantially aligned with the longitudinal axis of chamber 140. In preferred embodiments, at least a portion of the interior surfaces 141, 142, 145, and/or 147 of housing 112 that define chamber 140 are sufficiently reflective (e.g., characterized by an emissivity of less than 0.1, preferably 0.05) so that not only microwaves, but also some of the radiant energy generated during melting operations, are reflected back into chamber 140 in order to enhance melting performance.

Chamber 140 generally has a diameter that is determined by the distance between the interior surface 141 on one side of chamber 140 and the interior surface 142 on the other side of chamber 140. The length of chamber 140 is determined by the distance between plate 126 at the entrance to chamber 140 and plate 144 positioned at the exit from chamber 140. The diameter of chamber 140 as measured between the interior surface 141 on one side of melting zone 124 and the interior surface 142 on the other side of melting zone 124 is preferably equal to an integer multiple of the wavelength of the microwaves being used for processing. Providing chamber 140 with such a diameter helps ensure that the microwaves will

resonate inside chamber 140 to achieve uniform energy distribution and efficient melting performance. Preferably, such diameter is 2 to 5 times, and more preferably 2 to 3 times, the wavelength of the microwaves. For example, for 2.45 GHz microwaves, the diameter of chamber 140 is preferably 10.75 cm. Principles for determining suitable geometry characteristics of a microwave cavity such as chamber 140 are described, for example, in Metaxas, "Industrial Microwave Heating", Peter Peregrinus Ltd., London (1983).

The length of chamber 140 is less critical than the diameter. In fact, chamber 140 may be provided with any suitable length as desired to ensure that the polymer residence time in chamber 140 is long enough for melting to be accomplished. The preferred length of chamber 140 can be determined according to the desired electric field strength within the volume of material being heated. The field strength should be high enough to effect reasonable rates of heating but should not be so high as to result in breakdown and electric discharge (arcing) inside chamber 140. To achieve this goal, preferred electric fields are on the order of about 375 kV/m for power levels on the order of 6 kW. Given this field strength, and for an apparatus in which 2.45 GHz microwave energy is being used at a power output level of 6 kW, use of a chamber 140 having a length in the range from 20 cm to 100 cm, preferably about 40 cm to 50 cm, would be suitable for processing a wide range of different polymers. See generally Metaxas, "Industrial Microwave Heating", Peter Peregrinus Ltd., London (1983) at page 72.

In particularly preferred embodiments of the invention, microwave transparent liner 150 is provided in chamber 140. Use of microwave transparent liner 150 confines the flowing material being processed to the core region of chamber 140, where microwave energy distribution is at a maximum. Accordingly, liner 150 promotes more uniform heating, transport, and melting of such material. In the absence of liner 150, polymer material closer to sidewall 114 may have a tendency to be too cool whereas polymer material in the center of chamber 140 may be too hot. The resultant temperature gradient may tend to have an adverse impact upon flow characteristics through melting zone 124. The polymer material could also burn or otherwise degrade.

Liner 150 is provided proximal to sidewall 114, but does not line all of bottom 116. No liner is needed proximal to such portions of bottom 116, because the polymer material is typically fully melted by the time the polymer material reaches that part of chamber 140.

Liner 150 generally is formed from a microwave transparent material that not only absorbs a relatively small percentage of the microwave energy as the microwaves travel through liner 150, but also is substantially temperature resistant so that the material will not deform, melt, or otherwise degrade during melting operations. As used herein, the term "microwave transparent" means that the material has a relative complex permittivity such that less than 1%, and more preferably less than 0.01% of the microwave energy traveling through the material is absorbed when tested according to ASTM D2520-95 Complex Permittivity (Dielectric Constant) of Solid Electrical Insulating materials at Microwave Frequencies and Temperatures at 1650°C, Test Method B (1997). A wide variety of temperature resistant, microwave transparent materials suitable for forming liner 150 are known and include the so-called low loss ceramics, quartz, glass, porcelain, alumina, combinations of these, and the like.

The thickness of the walls of liner 150 will depend upon a variety of factors including the diameter of chamber 140, the material from which liner 150 is to be formed, the power output setting of microwave source 137, the frequency of the microwave radiation generated by microwave source 137, and the like. In preferred embodiments of the invention operating at 2.45 GHz and 6 kW, and in which chamber 140 has a diameter of 10.75 cm and liner 150 is formed from quartz or a low loss ceramic, forming liner 150 with a wall thickness in the range from 2.4 to 2.7 cm, preferably 2.55 to 2.65 cm, would be suitable.

The rotational speed of feed screw 128 generally determines the pressure in chamber 140. Desirably, melting occurs in chamber 140 at a relatively low pressure that is effective to develop sufficient force to transport polymer material through chamber 140. It is particularly desirable to match the flow rate of polymer material with the heating rate so that material enters chamber 140 through plate 126 at substantially the same rate that material leaves chamber 140 through

plate 144. If the force is too low, however, the residence time in chamber 140 may be too long and polymer materials being processed could burn or otherwise degrade. On the other hand, if the pressure is too high, the polymer feed rate will be too high to achieve sufficient melting. Accordingly, melting preferably is carried out in chamber 140 under a relatively low pressure in the range from about 2 kg/cm^2 to about 40 kg/cm^2, preferably 2 kg/cm^2 to 20 kg/cm^2. In the practice of the present invention, the pressure applied to material in chamber 140 may be determined as the pressure of the material at the exit port of chamber 140, i.e., at plate 144.

After melting, molten polymer is transferred from melting unit 104 to transport unit 106 through conduit 108. Transport of molten polymer between melting unit 104 and transport unit 106 may be accomplished using any suitable motivating means such as gravity, a pump, or the like. As shown in Fig. 6, melt pump 110 is used to accomplish such transport. Melt pump 110 performs at least two important functions. Firstly, melt pump 110 helps control the flow rate of molten material transferred to transport unit 106. Additionally, melt pump helps homogenize the molten material as well. Although melt pump 110 is preferred, other devices, such as a check valve, could also be used.

Transport unit 106 includes cylindrical housing 152 enclosing metering chamber 154 for holding a metered amount of molten polymer. Transport unit 106 is further provided with piston 156 which is capable of reciprocating movement inside housing 152 in directions along the longitudinal axis of transport unit 106. Piston 156 is disposed so that movement of piston 156 in the direction of arrow 158 forces molten polymer 160 through outlet passage 162 to a point of use. Because the operation of piston 156 acts in intermittent fashion once each piston cycle to force molten polymer to the point of use, transport unit 106 incorporating piston 156 is most effectively used for injection molding applications. On the other hand, if it is desired to provide molten polymer to a point of use involving an extrusion die, then a melt pump or other similar transport device can be substituted for piston 156 in order to convey a continuous supply of molten polymer to the point of use.

Because metering chamber 154 is separate from and independently pressurizable relative to chamber 140, relatively high pressures suitable for injection molding or extrusion can be developed in metering chamber 154 without affecting the performance of melting operations. For example, relatively high pressures in the range from 10 kg/cm^2 to 2000 kg/cm^2, preferably 500 kg/cm^2 to 1000 kg/cm^2, can be easily developed in metering chamber 154 while lower pressures are maintained in chamber 140.

Fig. 7 shows another embodiment of a polymer processing apparatus 200 of the present invention that is generally similar to polymer processing apparatus 100 of Fig. 6 (for example, all parts of Fig. 7 also found in Fig. 6 bear the same identification number as the corresponding parts of Fig. 6 except that the identification numbers of Fig. 7 also include the suffix "A") , except that apparatus 200 further includes core member 202 positioned in chamber 140A. Core member 202 extends from plate 126A to plate 144A and has a surface 204 defining an inner surface for guiding polymer material in annular fashion through chamber 140A. Use of core member 202 further optimizes the heating performance of apparatus 200 by confining flowing material to an annular region of chamber 140A in which the energy distribution of the resonating microwaves is most uniform. Advantageously, core member 202 is made form a microwave transparent material as defined above so that the presence of core member 202 does not interfere with melting performance at all. When chamber 140A is a TM_{020} mode cavity operating at 2.45 GHz and having an inside diameter of 10.75 cm, liner 150 is made from quartz and has a thickness in the range from about 2.4 to 2.7 cm core member 202 preferably may have a radius in the range from 1.8 to about 2 cm.

In order to be able to optimize heating performance for differing materials and processing conditions when using the embodiments of the invention shown in Figs. 6 or 7, it may be desirable that liner 150 (or 150A as the case may be) and/or core member 202 (if any) are independently removable so that different sized parts can be inserted into place in chamber 140 (or 140A) as needed. This allows heating performance to be optimized for any kind of polymer being processed. On the other hand, for manufacturing practicability, it may be desirable

to use nonremovable liner and/or core member having characteristics that generally provide good heating performance for a range of materials over a range of operating conditions.

In embodiments of the invention including a liner (such as liner 150 or 150A) and/or a core member (such as core member 202), one or both of such components can be rotatable about the axis of chamber 140 (or 140A as the case may be) to assist with material transport or mixing. If both a liner and a core member are present and rotatable, such members can be adapted for co-rotation, counter-rotation, or both, as desired.

While this invention has been described with respect to preferred embodiments, the present invention can be further modified within the spirit and scope of this disclosure. This application is therefore intended to cover any variations, uses, or adaptations of the invention using its general principles. Further, this application is intended to cover such departures from the present disclosure as come within known or customary practice in the art to which this invention pertains and which fall within the limits of the appended claims.

WHAT IS CLAIMED IS:

1. A method of using microwave energy to process a composition comprising at least one meltable polymer, comprising the steps of:

    (a) transporting a charge comprising the composition into a cavity in which the charge can be irradiated with microwave energy;

    (b) while the charge is in the cavity, irradiating the charge with microwave energy under conditions effective to melt the polymer;

    (c) transporting the melted polymer from the cavity to a metering chamber; and

    (d) transporting the melted polymer from the metering chamber to a point of use.

2. The method of claim 1, wherein the cavity is a single mode microwave cavity.

3. The method of claim 1, wherein the cavity is a single mode microwave cavity and step (a) comprises transporting the charge along a path substantially corresponding to the path along which the microwave energy propagates in the cavity.

4. The method of claim 1, wherein the cavity is a multimode microwave cavity.

5. The method of claim 1, wherein step (b) occurs while applying a first pressure to the charge within a first pressure range, step (d) occurs while applying a second pressure to the charge within a second pressure range, and wherein the second pressure is greater than the first pressure.

6. The method of claim 5, wherein the first pressure range extends from about 2 kg/cm^2 to about 20 kg/cm^2 and the second pressure range extends from about 10 kg/cm^2 to about 2000 kg/cm^2.

7. The method of claim 5, wherein the first pressure range extends from about 3 kg/cm^2 to about 10 kg/cm^2 and the second pressure range extends from about 500 kg/cm^2 to about 1000 kg/cm^2.

8. The method of claim 1, wherein steps (a) and (b) occur while transporting the charge through the cavity under substantially steady state conditions.

9. The method of claim 1, wherein a transport mechanism comprising a piston is operationally coupled to the metering chamber such that movement of the piston is capable of causing transport of the melted polymer from the metering chamber to the point of use.

10. The method of claim 1, wherein the point of use is a cavity of an injection mold positioned in fluid communication with the metering chamber.

11. The method of claim 1, wherein the point of use is an extruder die positioned in fluid communication with the metering chamber.

12. The method of claim 1, wherein the cavity is a chamber in an electrically conductive housing, and wherein a microwave transparent material is provided as a lining on at least a portion of an interior surface of the housing so that the charge transported into the chamber does not directly contact said housing portion.

13. The method of claim 12, wherein the microwave transparent material comprises a material selected from quartz, a low loss ceramic, a glass, a porcelain, and combinations thereof.

14. The method of claim 12, wherein a core member is positioned in the cavity in a manner effective to define an annularly shaped pathway for the charge to be transported through the cavity, and wherein the core member comprises a microwave transparent material.

15. The method of claim 14, wherein the microwave transparent material of the core member comprises a material selected from quartz, a low loss ceramic, a glass, a porcelain, and combinations thereof.

16. The method of claim 1, wherein the charge comprises a nonpolar polymer and a sufficient amount of a microwave energy absorbing additive such that irradiation of the charge with microwave energy causes the polymer to melt.

17. The method of claim 16, wherein the charge comprises from about 0.01 to about 20 parts by weight of the microwave energy absorbing additive based upon 100 parts by weight of the polymer resin.

18. The method of claim 1, wherein the polymer is a thermoplastic resin.

19. The method of claim 10, further comprising the steps of:

(a) conveying the melted charge from the metering chamber to the cavity of the injection mold;

(b) allowing the melted charge to substantially solidify in the cavity of the mold; and

(c) removing the solidified article from the mold.

20. An apparatus capable of using microwave energy to process a composition comprising at least one meltable polymer, said apparatus comprising:

(a) an electrically conductive housing defining a microwave processing cavity;

(b) a microwave energy source operationally coupled to the cavity such that, while a charge of the composition is in the cavity, the charge can be irradiated with microwave energy under conditions effective to melt the polymer;

(c) a chamber in fluid communication with the cavity such that the melted polymer can be transported from the cavity to the chamber; and

(d) a transport mechanism operationally coupled to the chamber in a manner such that melted polymer in the chamber can be transported to a point of use.

21. The apparatus of claim 20, wherein the microwave processing cavity is a single mode microwave cavity.

22. The apparatus of claim 20, wherein the microwave processing cavity is a single mode microwave cavity positioned in the housing such that the composition can be transported through the housing along a path substantially corresponding to the path along which the microwave energy propagates in the cavity.

23. The apparatus of claim 20, wherein the cavity is a multimode microwave cavity.

24. The apparatus of claim 20, wherein the transport mechanism comprises a piston operationally coupled with the chamber such that movement of the piston is capable of causing transport of the melted polymer from the chamber to the point of use.

25. The apparatus of claim 20, wherein the point of use is a cavity of an injection mold positioned in fluid communication with the metering chamber.

26. The apparatus of claim 20, wherein the point of use is an extruder die positioned in fluid communication with the metering chamber.

27. The apparatus of claim 20, wherein the apparatus further comprises a microwave transparent material lining at least a portion of an interior surface of the housing such that a charge transported into the microwave processing cavity does not directly contact said housing portion.

28. The apparatus of claim 27, wherein the microwave transparent material comprises a material selected from quartz, a low pass ceramic, a glass, a porcelain, and combinations thereof.

29. The apparatus of claim 20, wherein the apparatus further comprises a core member positioned in the cavity in a manner effective to define an annularly shaped pathway for the charge to be transported through the cavity, and wherein the core member comprises a microwave transparent material.

30. A process of using microwave energy to process a composition comprising at least one meltable polymer, comprising the steps of:

(a) providing a rotatable member comprising a first cavity for holding a charge comprising a polymer resin;

(b) rotating the rotatable member to a first position such that the cavity is in communication with a supply comprising the polymer;

(c) delivering a charge comprising the polymer from the supply to the cavity;

(d) after delivering the charge to the cavity, irradiating the charge with microwave energy under conditions effective to melt substantially all of the polymer, wherein said irradiating step occurs after the rotatable member is rotated away from the first position;

(e) after melting the polymer, transporting at least a portion of the melted polymer to a metering chamber; and

(f) transporting the melted polymer from the metering chamber to a point of use.

31. The process of claim 30, wherein the rotatable member is rotatable into a plurality of positions comprising a first position, a second position, and a third position, wherein delivering of the charge to the cavity occurs when the rotatable member is in the first position, irradiating of the charge in the cavity occurs when the rotatable member is in the

second position, and transporting of the charge from the cavity to the metering chamber occurs when the rotatable member is in the third position.

32. The process of claim 30, wherein the rotatable member is rotatable into a plurality of positions comprising a first position and a second position, wherein delivering of the charge to the cavity occurs when the rotatable member is in the first position, irradiating of the charge in the cavity occurs when the rotatable member is rotating from the first position to the second position, and transporting of the charge from the cavity occurs when the rotatable member is in the second position.

33. The process of claim 30, wherein the rotatable member is substantially cylindrical and has first and second axial faces, and wherein the cavity is capable of being in open communication with the first axial face of said rotatable member in order to receive the charge.

34. The process of claim 33, wherein the rotatable member is disposed in a housing comprising a top housing section disposed proximal to the first axial face of the rotatable member and a bottom housing section disposed proximal to the second axial face of the rotatable member.

35. The process of claim 30, wherein movement of a piston causes transport of the charge from the cavity to the metering chamber.

36. The process of claim 30, wherein movement of a piston causes transport of the charge from the metering chamber to the point of use.

37. A process of using microwave energy to process a composition comprising at least one meltable polymer, comprising the steps of:

(a) providing a rotatable member, wherein the rotatable member comprises first, second, and third cavities, wherein rotation of the rotatable member causes each of the cavities to move sequentially

through successive delivery, irradiating, and transport positions of a processing cycle, wherein such cycle is successively repeated by each cavity as the rotatable member rotates, and wherein the one cavity in the delivery position is capable of receiving a charge comprising the polymer, the one cavity in the irradiating position holds a charge of the composition during irradiation, and the one cavity in the transport position holds a charge comprising a substantially melted polymer resin;

(b) delivering a charge comprising a substantially unmelted polymer resin to the cavity in the delivery position;

(c) irradiating the charge held in the cavity disposed in the irradiating position with an amount of microwave energy sufficient to melt substantially all of the polymer resin of said charge;

(d) transporting at least a portion of the charge held in the cavity in the transport position to a metering chamber such that said cavity is capable of receiving an additional charge comprising a polymer resin;

(e) injecting the charge from the metering chamber into a mold comprising an internal volume having a shape corresponding to the article to be molded;

(f) rotating the rotatable member such that each of the cavities is advanced sequentially to the next corresponding position of the processing cycle; and

(g) repeating steps (b) through (f) a plurality of times.

38. An apparatus for processing a composition comprising at least one meltable polymer, comprising:

(a) a rotatable member comprising a cavity for holding a charge of the composition;

(b) a microwave energy source operationally coupled to the cavity such that the charge in the cavity can be irradiated with microwave energy under conditions effective to melt the polymer;

(c) a metering chamber capable of being in fluid communication with the cavity so that the charge can be transported from the cavity to the metering chamber; and

(d) a first transport mechanism operationally positioned in the apparatus such that the first transport mechanism is capable of transporting the charge from the metering chamber to a point of use.

39. The apparatus of claim 38, wherein the rotatable member is rotatable into a plurality of positions comprising a first position, a second position, and a third position, wherein the charge is deliverable to the cavity when the rotatable member is in the first position, the charge in the cavity is irradiatable when the rotatable member is in the second position, and the charge is transportable from the cavity to the metering chamber when the rotatable member is in the third position.

40. The apparatus of claim 38, wherein the member is rotatable into a plurality of positions comprising a first position and a second position, wherein the charge is deliverable to the cavity when the rotatable member is in the first position, the charge is irradiatable in the cavity when the rotatable member is rotating from the first position to the second position, and the charge is transportable from the cavity when the rotatable member is in the second position.

41. The apparatus of claim 38, wherein the member is rotatable and comprises first, second, and third cavities, wherein rotation of the rotatable member causes each of the cavities to move sequentially through successive delivery, irradiating, and transport positions of a processing cycle, wherein such cycle is successively repeated by each cavity as the rotatable member rotates, and wherein the one cavity in the delivery position is capable of receiving a charge comprising a polymer resin, the one cavity in the irradiating

position holds a charge during irradiation, and the one cavity in the transport position holds a charge comprising a substantially melted polymer resin.

42. The apparatus of claim 38, wherein the apparatus further comprises a second transport mechanism operationally positioned in the apparatus such that the second transport mechanism is capable of transporting at least a portion of the charge comprising the melted polymer resin from the cavity to the metering chamber.

43. The apparatus of claim 38, wherein the first transport mechanism comprises a piston operationally disposed in the first transport mechanism such that movement of the transport piston is capable of causing transport of the charge from the metering chamber to the point of use.

44. An apparatus capable of using microwave energy to process a composition comprising at least one meltable polymer, said apparatus comprising:

(a) an electrically conductive housing defining a microwave processing cavity having a length extending from a material feed port and a material exit port;

(b) a source of microwave energy operationally coupled to the cavity such that the microwave energy propagates in single mode fashion along the length of the microwave processing cavity and such that, while a charge of the composition is in the cavity, the charge can be irradiated with the microwave energy under conditions effective to melt the polymer; and

(c) a microwave transparent material lining at least a portion of an interior surface of the housing.

45. The apparatus of claim 44, wherein the housing is cylindrically shaped.

46. The apparatus of claim 44, wherein the microwave transparent material comprises a material selected from quartz, a low pass ceramic, a glass, a porcelain, and combinations thereof.

47. The apparatus of claim 45, wherein the apparatus further comprises a core member positioned in the cavity in a manner effective to define an annularly shaped pathway for the charge to be transported through the cavity, and wherein the core member comprises a microwave transparent material.

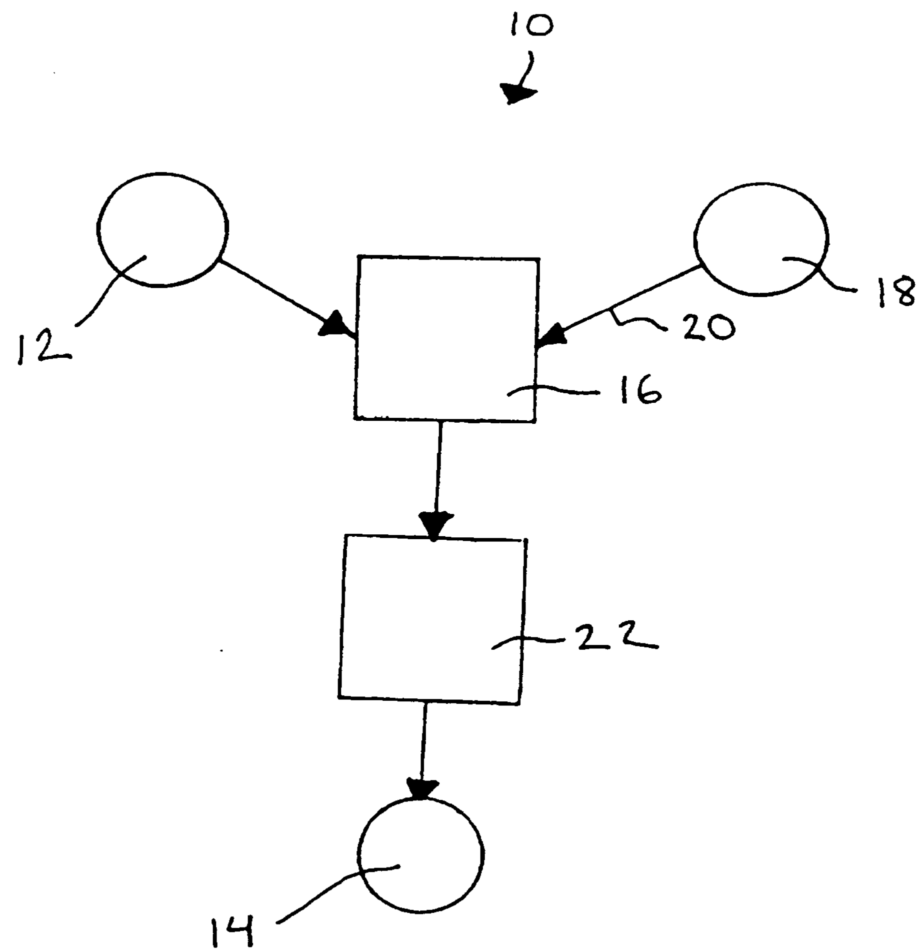


Fig. 1

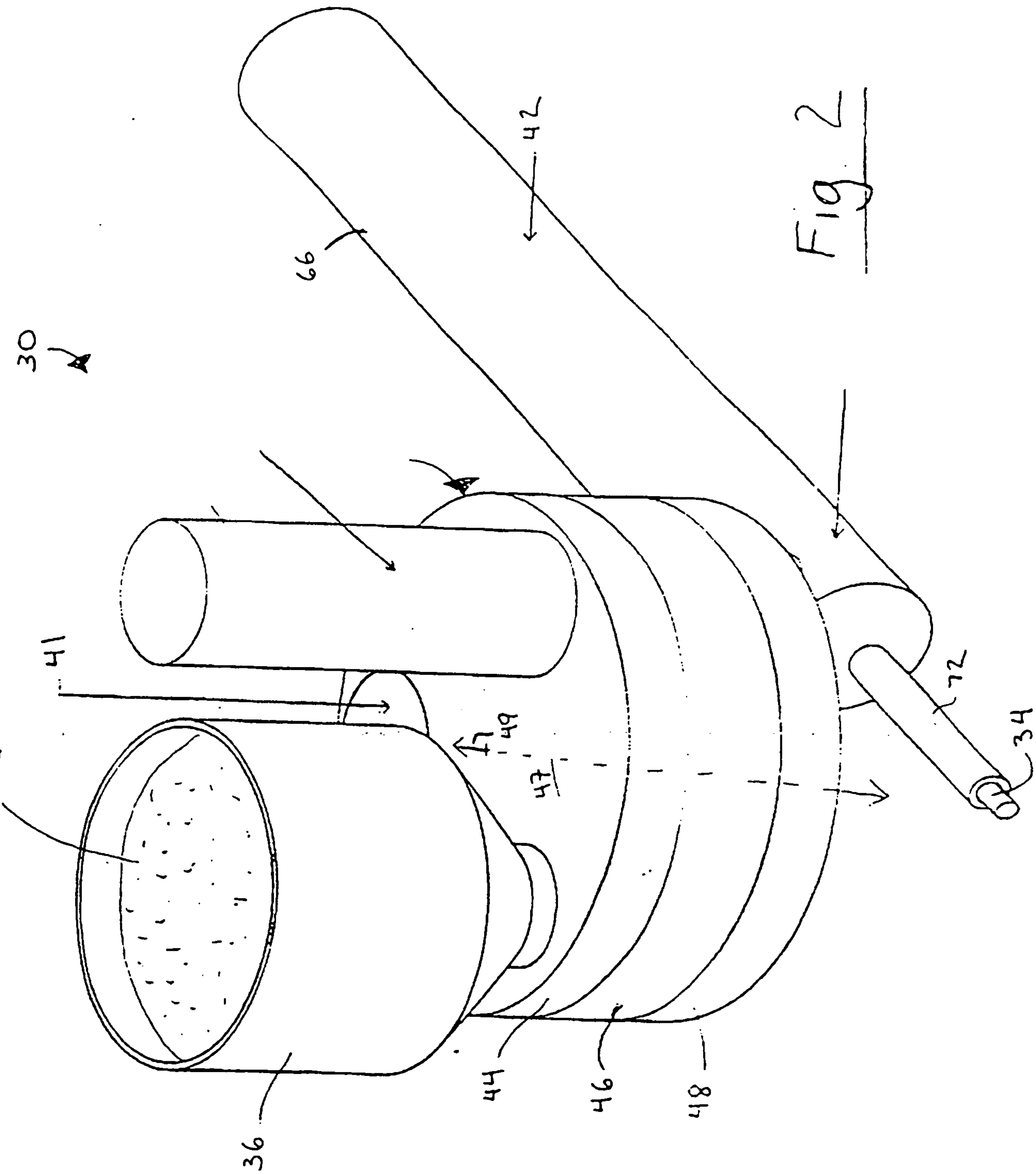


Fig 2

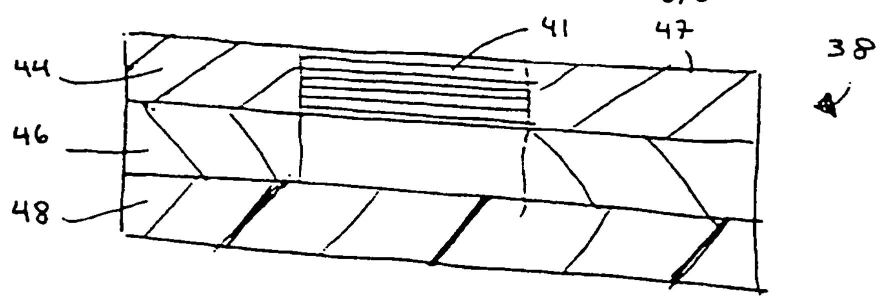
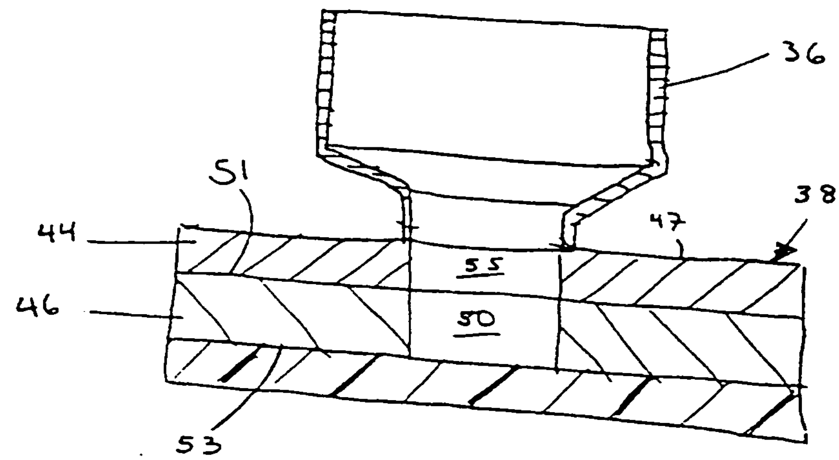


Fig. 3



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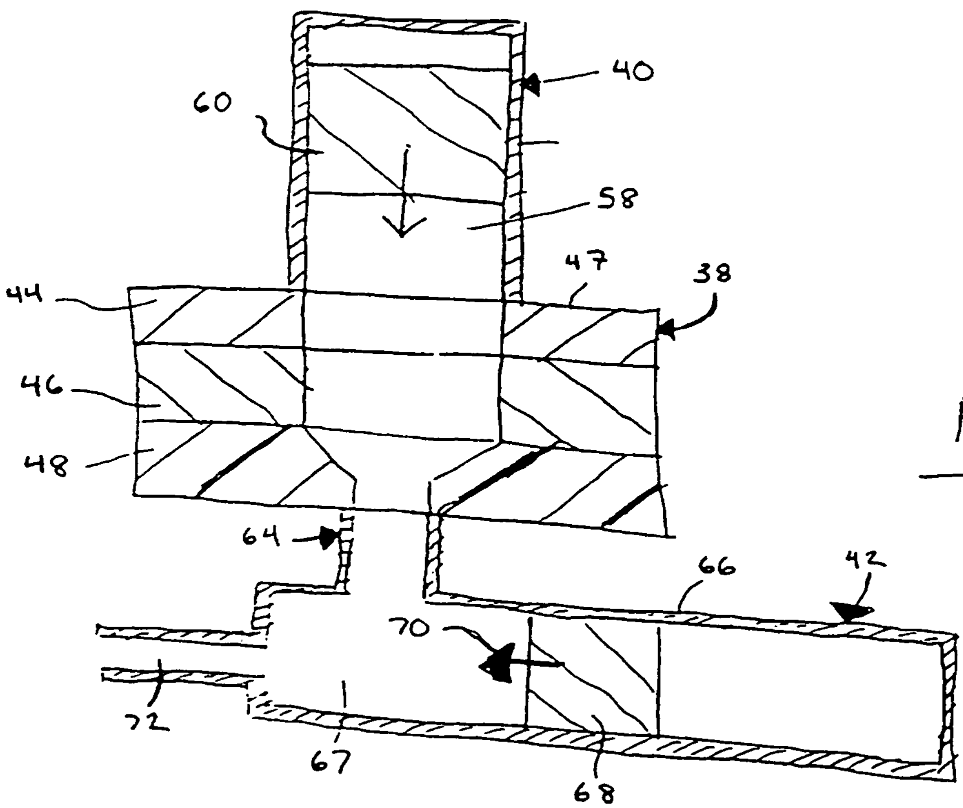

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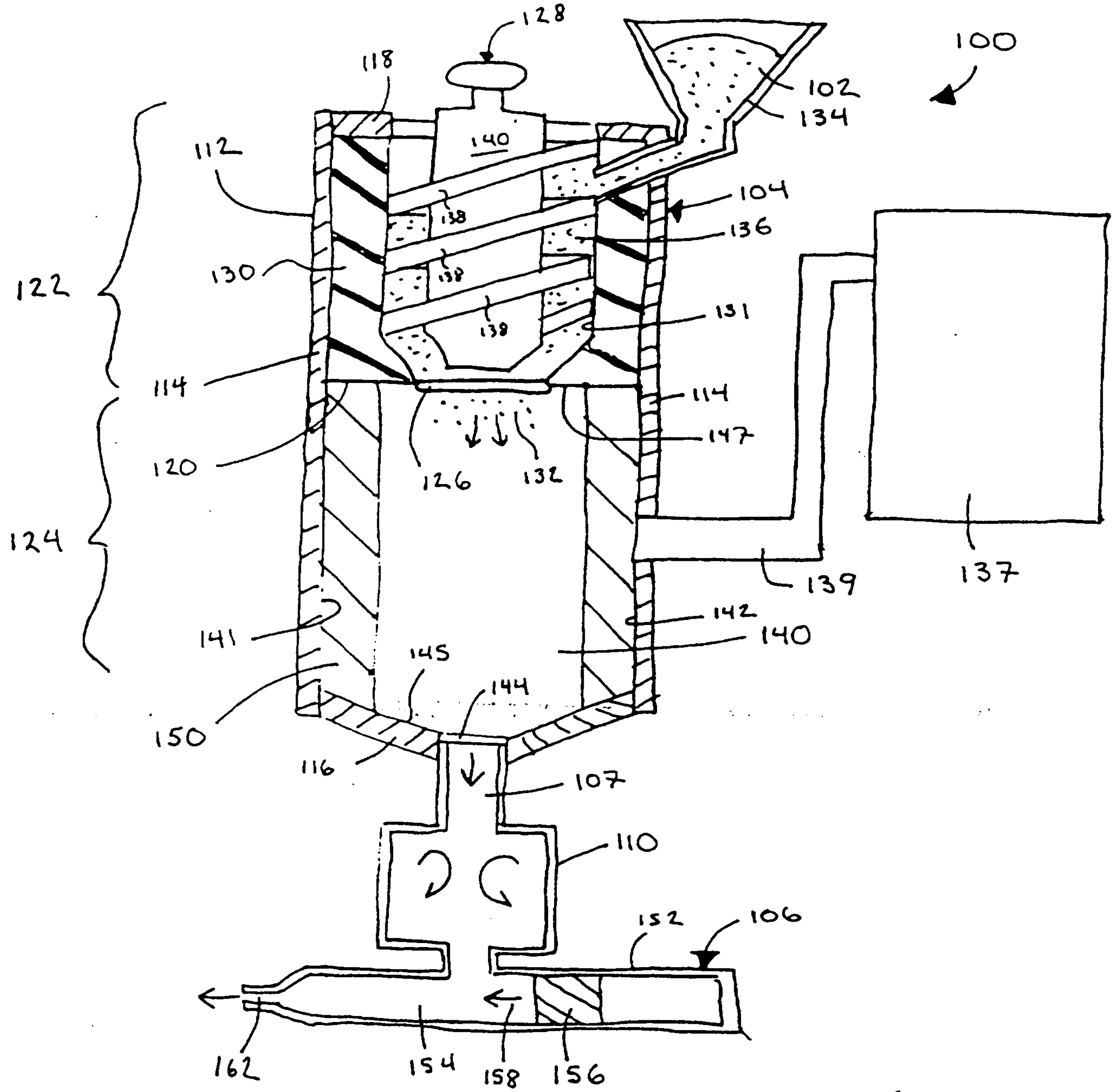

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Fig. 6

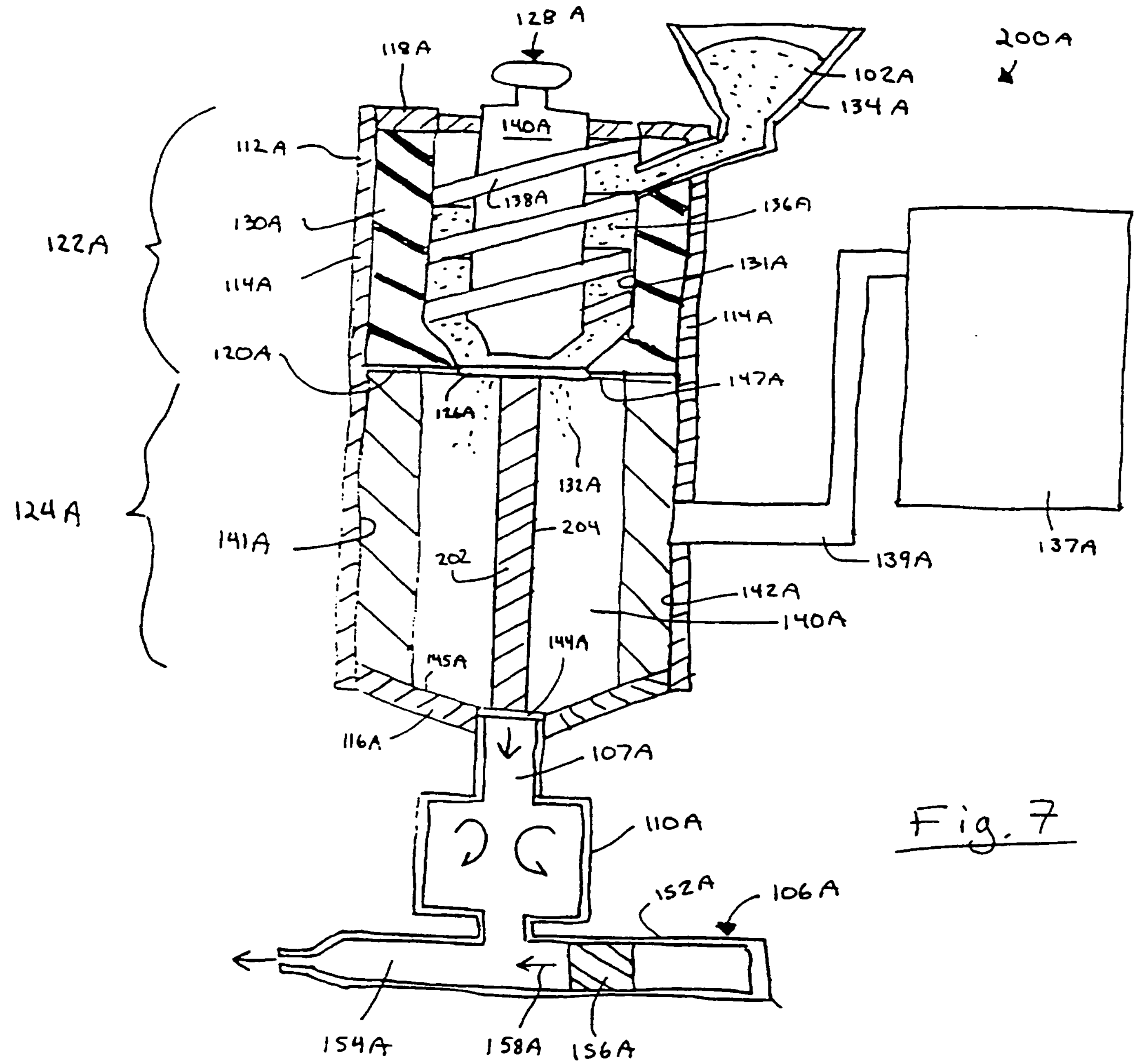
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Fig. 7

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 97/17399

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 B29B13/08 B29C31/06 B29C35/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 B29B B29C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 760 228 A (KUDO MINORU) 26 July 1988 see the whole document	1,2, 8-13, 18-21, 24-28, 44-46
X	US 4 577 078 A (NODA YASUMASA ET AL) 18 March 1986 see column 3, line 56 - column 4, line 52; claims 1,12; figures 6,10	1,2,9, 10,12, 18-21, 24,25, 27,44,45
A	US 4 003 554 A (CHAUFFOUREAUX JEAN) 18 January 1977 see the whole document	1-29, 44-47

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[X] Further documents are listed in the continuation of box C

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Date of the actual completion of the international search	Date of mailing of the international search report
22 January 1998	02/02/1998

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Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No
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CORRECTED VERSION*

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WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : B29B 13/08, B29C 31/06, 35/08 — A1

(11) International Publication Number: WO 98/14314

(43) International Publication Date: 9 April 1998 (09.04.98)

(21) International Application Number: PCT/US97/17399

(22) International Filing Date: 26 September 1997 (26.09.97)

(30) Priority Data:
60/027,072 30 September 1996 (30.09.96) US

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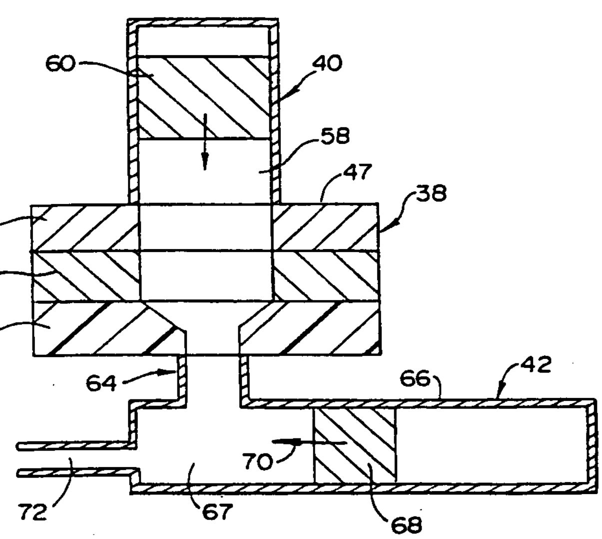
(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, US, UZ, VN, ARIPO patent (GH, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: MICROWAVE PROCESSING SYSTEM FOR POLYMERS



(57) Abstract

Polymer processing systems and methods which use microwave energy to achieve extremely rapid, efficient melting and/or softening of polymer materials. After rapid melting and/or softening is achieved, the molten polymer may then be pressurized for transport to an injection mold, an extrusion die, or the like, as desired. Microwave melting occurs so rapidly, that significant reductions in cycle time would be achieved by the present invention. Additionally, the use of microwave energy for melting is economically advantageous, because microwave energy sources are generally less costly and use energy more efficiently than conventional melting systems.

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MICROWAVE PROCESSING SYSTEM FOR POLYMERS

FIELD OF THE INVENTION

The present invention relates to a polymer processing apparatus and method for melting a polymer and then transporting the melted polymer to a point of use, such as an injection mold, an extrusion die, or the like. More specifically, the present invention relates to a polymer processing apparatus and method in which microwave energy is used to accomplish melting in one chamber and transport of the melted polymer to a point of use is accomplished from another independently pressurizable chamber.

BACKGROUND OF THE INVENTION

Articles formed from thermoplastic and thermosetting polymer resins are found everywhere and are used in an incredibly wide variety of applications. In spite of their widespread and divergent uses, most polymeric articles are formed using generally similar processing techniques. In a typical molding process, for example, a polymer resin is provided in a solid, pelletized form. The polymer resin pellets are initially melted or softened, and then the melted or softened material is brought into contact with an extrusion die or mold in which the polymer assumes the molded or extruded form of the intended article.

With respect to injection molding, cycle time refers collectively to the period of time it takes to first melt a given charge of polymer resin, then to transport the molten polymer into a mold, then to allow the melt to solidify in the mold to form the molded article, and finally to open the mold and remove the molded article. Faster cycle times are generally desired, because a higher output of molded articles can be produced per unit of time.

One factor affecting cycle time concerns the technique which is used to accomplish melting of the polymer material. With some melting approaches, the time required for melting is relatively long, thus adversely affecting cycle time.

Additionally, some melting approaches do not use energy efficiently, increasing the amount of energy required, and therefore the expense, for melting as compared to a process that is more energy efficient. Some melting approaches also require complex and/or expensive machinery, thus further increasing the costs associated with polymer processing. For example, many conventional injection molding and extrusion approaches rely primarily upon thermal conductivity of the material being heated in order to achieve melting. Because of limitations in the rate of heat transfer using such an approach, the flow rate of polymer material, and thus overall throughput of the polymer processing equipment, is also limited. Conventional heating also typically results in non-uniform heating throughout the bulk volume of the material being processed, and this non-uniformity typically must be overcome by constant motion, agitation, or stirring of the material been heated.

It would be desirable, therefore, to provide an approach which melts or softens polymer resins faster so that cycle time could be reduced. It would also be desirable if such an approach used energy more efficiently and required less complex, less expensive machinery so that the costs of polymer processing could be reduced.

Another factor affecting cycle time concerns the technique which is used to transport the melted polymer from the melting chamber to the injection mold or extrusion die. It would be desirable to provide an approach which accomplishes transport faster so that cycle time could be reduced. It would also be desirable if such an approach required less complex, less expensive machinery so that the costs of transporting the polymer melt could be reduced.

SUMMARY OF THE INVENTION

The present invention advantageously provides polymer processing systems and methods which use microwave energy to achieve extremely rapid, efficient melting and/or softening of polymer materials. An important advantage of microwave heating is the ability to heat polymer material volumetrically. That is, heat is transferred to the material throughout its cross-section by radiation rather than by thermal conduction. The rate of heat transfer is not limited by the thermal

conductivity of the material being heated, thus heat transfer occurs much faster. Microwave melting occurs so rapidly, that significant reductions in cycle time would be achieved by the present invention. Additionally, the use of microwave energy for melting is economically advantageous, because the system of the present invention uses energy more efficiently than conventional melting systems. Heating uniformity is also improved by microwave heating.

Further, preferred embodiments of the present invention include separate melting and metering chambers that can be pressurized independently of each other. This approach allows microwave melting to occur under a first, relatively low pressure, while molten polymer in the metering chamber can be pressurized to a second, relatively high pressure more suitable for extrusion, injection molding, or the like. This greatly simplifies the structure and construction of the apparatus.

In preferred embodiments of the invention suitable for injection molding operations, a piston or melt pump may be used to pressurize and convey the molten polymer from the metering chamber to the cavity of the injection mold. By using a piston or melt pump to accomplish such transport, rather than screws which are more conventionally used, cycle time and machinery costs are significantly reduced.

Preferred embodiments of the present invention involve conveying a continuous flow of polymer material through a conduit that not only serves as a passage for the polymer, but also serves as a single mode microwave cavity in which microwave energy is propagated along a path that substantially coincides with the path taken by the polymer being conveyed. Thus, the polymer flows through the conduit in the region where the electronic field, and hence heating efficiency, is at a maximum. Accordingly, this approach provides faster, more efficient, more flexible polymer melting capabilities. For example, both polar and nonpolar polymers may be quickly and continuously melted using the approach of the present invention. In contrast, many polymers, especially nonpolar polymers, are often difficult to melt with microwaves in a reasonable amount of time in a continuous process that involves conveying the polymer through a multimode

microwave cavity. As another advantage, residence time in the single mode microwave cavity of the present invention is also easily controlled merely by adjusting the length of the cavity. To increase residence time, for example, the length of the cavity can be increased without requiring any drop in material flow rate.

In many of the previously proposed schemes involving continuous flow of polymer through a conduit comprising a flux of microwave energy, the more centrally located flow has a tendency to overheat relative to portions of the flow closer to the conduit walls. Such nonuniform heating creates the danger that portions of the polymer will be burned, or otherwise degraded. Preferred embodiments of the invention rely upon a microwave transparent liner (e.g., a low loss ceramic such as quartz) to overcome both of these drawbacks. The liner helps to confine the polymer flow to conduit regions in which the microwave energy distribution is sufficiently uniform so that polymer burning or other degradation is easily avoided.

In one aspect, the present invention relates to a method of using microwave energy to process a composition comprising at least one meltable polymer. A charge comprising the composition is transported into a cavity in which the charge can be irradiated with microwave energy. While the charge is in the cavity, the charge is irradiated with microwave energy under conditions effective to melt the polymer. The melted polymer is then transported from the cavity to an independently pressurizable metering chamber. The melted polymer is then transported from the metering chamber to a point of use.

In another aspect, the present invention relates to an apparatus capable of using microwave energy to process a composition comprising at least one meltable polymer. The apparatus includes an electrically conductive housing defining a microwave processing cavity. A microwave energy source is operationally coupled to the cavity such that, while the charge is in the cavity, the charge can be irradiated with microwave energy under conditions effective to melt the polymer. A chamber is in fluid communication with the cavity such that the melted polymer can be transported from the cavity to the chamber. A transport

mechanism is operationally coupled to the chamber in a manner such that melted polymer in the chamber can be transported to a point of use.

In another aspect, the present invention relates to a process of using microwave energy to process a composition comprising at least one meltable polymer. A rotatable member is provided comprising a first cavity for holding a charge comprising a polymer resin. The rotatable member is rotated to a first position such that the cavity is in communication with a supply comprising the polymer. A charge comprising the polymer from the supply is delivered to the cavity. After delivering the charge to the cavity, the charge is irradiated with microwave energy under conditions effective to melt substantially all of the polymer, wherein said irradiating step occurs after the rotatable member is rotated away from the first position. After melting the polymer, at least a portion of the melted polymer is transported to a metering chamber. The melted polymer is transported from the metering chamber to a point of use.

In another aspect, the present invention relates to a process of using microwave energy to process a composition comprising at least one meltable polymer. A rotatable member is provided, wherein the rotatable member comprises first, second, and third cavities, wherein rotation of the rotatable member causes each of the cavities to move sequentially through successive delivery, irradiating, and transport positions of a processing cycle, wherein such cycle is successively repeated by each cavity as the rotatable member rotates, and wherein the one cavity in the delivery position is capable of receiving a charge comprising the polymer, the one cavity in the irradiating position holds a charge of the composition during irradiation, and the one cavity in the transport position holds a charge comprising a substantially melted polymer resin. A charge comprising a substantially unmelted polymer resin is delivered to the cavity in the delivery position. The charge held in the cavity disposed in the irradiating position is irradiated with an amount of microwave energy sufficient to melt substantially all of the polymer resin of said charge. At least a portion of the charge held in the cavity in the transport position is transported to a metering chamber such that said cavity is capable of receiving an additional charge comprising a polymer resin. The charge from the metering

chamber is injected into a mold comprising an internal volume having a shape corresponding to the article to be molded. The rotatable member is rotated such that each of the cavities is advanced sequentially to the next corresponding position of the processing cycle. Steps (b) through (f) are repeated a plurality of times.

In another aspect, the invention relates to an apparatus for processing a composition comprising at least one meltable polymer. The apparatus includes a rotatable member comprising a cavity for holding a charge of the composition. A microwave energy source is operationally coupled to the cavity such that the charge in the cavity can be irradiated with microwave energy under conditions effective to melt the polymer. A metering chamber is capable of being in fluid communication with the cavity so that the charge can be transported from the cavity to the metering chamber. A first transport mechanism is operationally positioned in the apparatus such that the first transport mechanism is capable of transporting the charge from the metering chamber to a point of use.

BRIEF DESCRIPTION OF THE DRAWINGS

The above-mentioned and other features and advantages of this invention, and the manner of attaining them, will become more apparent and the invention will be better understood by reference to the following description of an embodiment of the invention taken in conjunction with the accompanying drawings, wherein:

Fig. 1 is a schematic representation of a system for melting polymers according to the present invention;

Fig. 2 is a perspective schematic view of a polymer processing apparatus according to one embodiment of the present invention;

Fig. 3 is a side sectional view of the main processing unit used in the embodiment of Fig. 2 in which a cavity is shown in the irradiating position;

Fig. 4 is a side sectional view of the hopper and main processing unit of the embodiment of Fig. 2 in which a cavity is shown in the delivery position;

Fig. 5 is a side sectional view of the transfer cylinder, injection mechanism, and main processing unit of the embodiment of Fig. 2 in which a cavity is shown in the transport position;

Fig. 6 is a side sectional view of a polymer processing apparatus according to an alternative embodiment of the present invention; and

Fig. 7 is a side sectional view of a polymer processing apparatus according to an alternative embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The various aspects of the present invention will now be described with reference to the particular embodiments of the present invention shown in Figs. 1 through 7. However, the embodiments disclosed below are not intended to be exhaustive or to limit the invention to the precise forms disclosed in the following detailed description.

Fig. 1 is a schematic representation of a polymer processing system 10 incorporating the principles of the present invention. System 10 is adapted to melt a feed 12 comprising at least one polymer resin, and then deliver the molten polymer to a point of use 14, which may be the cavity of an injection mold, an extrusion die, or the like. Advantageously, a wide variety of thermosetting and thermoplastic polymer resins known to be suitable for molding or extrusion can be processed using system 10, although the use of thermoplastic materials is commonly preferred for injection molding applications. Examples of such thermoplastic and/or thermosetting materials suitable in the practice of the present invention include polyethylene; polypropylene; polyether; polyester; a copolymer comprising butadiene and styrene; a copolymer comprising acrylonitrile, butadiene, and styrene (ABS); polyurethane; vinyl resin such as polyvinyl chloride; polyamide (such as the various polyamide resins referred to as "nylons"); epoxy resin, phenolic resin; polyimides; polyamideimides; vulcanized rubbers (synthetic and natural); fluorinated polyolefins such as polytetrafluoroethylene and polyvinyldene fluoride; acrylic resin such as polymethylmethacrylate; polysulfones, acetal resin; bismaleimide resin; cellulosic resin; ketone based resin; liquid crystal polymer;

melamine-formaldehyde resin; polycarbonate; polyetherimide; other polyalkylene resin such as polymethylpentene; nitrile resin; polyphthalamide; silicone resin; urea resin; sulfone-based resin; combinations thereof, and the like. For a description of such resins, see, e.g., Plastics Handbook, edited by Modern Plastics, McGraw-Hill, Inc., 1994.

Generally, relatively polar polymers such as polyvinyl chloride, polyamide, polyurethane, epoxy, polyimide, vulcanized rubber, ABS, and the like, tend to absorb enough microwave energy by themselves so that microwave melting can be accomplished without the use of microwave energy absorbing additives. On the other hand, relatively nonpolar polymers such as polyolefins, polyester, polystyrene, high impact polystyrene, polytetrafluoroethylene, allyl resin, styrenic resin, and the like, typically do not by themselves absorb significant amounts of microwave energy. As a result, irradiating such materials with just microwave energy may not be effective to achieve the desired melting or softening of such nonpolar materials. Accordingly, it is preferred that any such nonpolar polymer resin, or resins, are combined with an effective amount of a microwave absorbing additive, or "sensitizer" as such materials are referred to in the art. Advantageously, such an additive will absorb microwave energy, which heats the additive. Such heat is then thermally transferred to the nonpolar polymer resin, causing the polymer resin to melt or soften as desired. When the additive is homogeneously distributed throughout the bulk volume of the polymer, this heat transfer is extremely rapid.

The microwave absorbing additive generally may be any solid or liquid polar compound or combination of such compounds capable of absorbing and being heated by microwave energy and then thermally transferring the resultant heat energy to the polymer material to be processed. Such additives can be organic or inorganic. Organic polar compounds may be monomeric, oligomeric, or polymeric. Examples of representative classes of materials suitable for use as a microwave absorbing additive include any material known to function as an antistatic agent, carbon fibers, metal powder, color retardants of the type used in paint compositions, ultraviolet light absorbing materials commonly used in paint

compositions, metal hydroxides such as $Mg(OH)_2$, other inorganic salts such as $CaSO_4{\bullet}H_2O$ and $MgSO_4{\bullet}H_2O$; fatty acids; fatty acid esters; water; glyceryl esters; alcohols; amides; amines; hydroxylated amines such as ethanolamine; alkylene glycols; quaternary ammonium salts, low molecular weight polar polymers and oligomers having a weight average molecular weight in the range from 200 to 8000 such as polyethylene glycol and polyvinyl alcohol, combinations of these and the like. For food grade products, FDA-approved additives such as $Mg(OH)_2$, are particularly preferred.

Choosing an appropriate amount of the microwave absorbing additive will depend upon a variety of factors such as the polymer resin being processed, the identity of the additive being used, the microwave frequency, the power output level of the microwave energy source, and the like. In selecting an appropriate amount of the microwave absorbing additive, enough of the additive should be combined with the polymer resin such that substantially complete melting, or the desired degree of softening, of the resin is achieved. If too little of the microwave absorbing additive were to be used, an insufficient degree of melting or softening may occur. On the other hand, if too much is used, the physical properties of the resultant polymeric article may be impaired. Additionally, if too much of the additive were to be used, too much heat may be generated which might degrade or burn the polymer. Generally, using 0.01 to about 20, preferably 0.01 to about 5, parts by weight of the additive per 100 parts by weight of the polymer resin would be suitable in the practice of the present invention.

The microwave absorbing additive can be incorporated into feed 12 in any desired, convenient manner. For example, if the additive is a liquid, then pellets of the polymer and liquid can be "pre-tumbled" together in order to coat the pellets with the liquid. Alternatively, if the additive is a solid, then the additive and the polymer may be compounded together to achieve a homogeneous admixture of the ingredients. The use of microwave energy absorbing additives to allow nonpolar polymer resins to be heated with microwave energy has been described in

the art. See, e.g., U.S. Pat. Nos. 4,288,399; 4,360,607; 4,400,483; 4,840,758; and 5,446,270.

System 10 generally comprises a first stage of operation represented by microwave cavity 16 in which feed 12 is melted using microwave energy, and a second stage of operation 22 in which the molten feed is pressurized for transport to point of use 14. This "multistage" approach allows microwave melting to occur at relatively low pressure, greatly simplifying the construction of microwave cavity 16 relative to a single-stage system in which microwave melting and pressurization for transport occur in the microwave cavity.

Microwave cavity 16 is generally defined by walls formed from electrically conductive material(s) that electrically shield the cavity, thereby substantially preventing microwaves from escaping from microwave cavity 16. Representative examples of such materials are well-known in the art and include corrosion-resistant metals, metal alloys, intermetallic compositions, combinations of these, and the like. Preferred examples of such materials include aluminum, stainless steel, copper, die-cast zinc, combinations of these, and the like.

Microwave cavity 16 can be either a single mode microwave cavity or a multi-mode microwave cavity, as desired. The term "mode" refers to the specific electromagnetic field pattern that develops inside a microwave cavity. The mode pattern is governed primarily by the internal geometry of the cavity and the wavelength of the electromagnetic energy which propagates within the cavity. A multi-mode cavity generally refers to a microwave cavity that is relatively large compared to the wavelength of microwave energy, such as, for example, a household microwave oven. A multi-mode microwave cavity generally contains multiple mode patterns which tend to be somewhat random. The electric field strength throughout a multi-mode cavity, therefore, is typically random and difficult to control. When materials are heated in a multi-mode cavity, heating uniformity can be improved by constant motion, agitation, or stirring of the material.

In contrast, a single mode microwave cavity refers to a smaller cavity that is capable of supporting only a single well-defined mode pattern which tends to be very regular and predictable. When materials are heated in a single-mode

cavity, good heating uniformity results without requiring constant motion, agitation, or stirring of the material being processed. As compared to a multi-mode cavity, heating is significantly more uniform and easier to control in a single mode cavity. In the practice of the present invention, a single mode microwave cavity is generally more suitable for use in a continuous process (see for example the embodiments of the present invention described below in connection with Figs. 6 and 7), and a multi-mold microwave cavity is generally more suitable for use in a batch process (see for example the embodiment of the present invention described below in connection with Figs. 2-5).

Microwave cavity 16 can be provided with any suitable shape and dimensions. The precise configuration of microwave cavity 16 will depend upon a variety of factors including, for example, the frequency of the microwave energy, the residence time required to accomplish melting, whether cavity 16 is intended for multimode or single mode operation, whether cavity 16 is intended for batch and continuous processing, and the like. Preferred microwave cavities 16 of the invention, nonetheless, are provided with a cylindrical shape, because cylindrically-shaped cavities can be relatively easily provided with dimensions effective to resonate at the frequency of the microwave energy supplied by microwave source 18 so as to promote even energy distribution in microwave cavity 16. Depending upon the mode of operation, microwaves can be propagated along the longitudinal axis of such cylindrically-shaped cavities, generally perpendicular to such axis, or at an angle to such axis, as desired.

In particularly preferred embodiments of the present invention, microwave cavity 16 is cylindrical in shape and is configured to provide a single mode pattern which places the electric field parallel to the axis of the cavity. The material being heated is then conveyed through the cavity in line with the axis and electric field in order to achieve the maximum heating efficiency. Even more preferably, in order to further optimize heating performance, a cylindrically-shaped, single mode microwave cavity of the present invention has the so-called TM_{020} mode configuration in which a peak electric field exists at the center axis of the

cavity with another peak forming an annulus about the center axis. The electric fields in both peaks thus are parallel to the center axis of the cylindrical cavity.

As an option, at least a portion and preferably substantially all of the interior surfaces of the electrically conductive walls defining microwave cavity 16 are sufficiently reflective so that at least a portion of the radiant heat energy generated during polymer melting is reflected back into microwave cavity 16 in order to promote more effective melting of the polymer resin(s) being processed. The interior surfaces of the cavity walls are preferably as reflective as practical circumstances allow. Although a surface cannot be too reflective from a technical perspective, there is a level of reflectivity beyond which the incremental improvement in performance offered by additional improvement in reflectivity characteristics may not justify the extra cost of attaining such improvement.

Advantageously, using the combination of both microwave energy and reflected radiant energy provides much better melting performance than using microwave energy alone, particularly when nonpolar polymers are being processed. For example, some non-polar polymers may not melt upon irradiation with just microwave energy alone unless relatively large quantities of a microwave energy absorbing additive is blended with, or otherwise incorporated into, the non-polar polymer. However, when the interior surfaces of the microwave cavity walls are highly reflective such that both microwave energy and reflected radiant energy are used to accomplish melting, many kinds of non-polar polymers can be melted with lesser quantities of such additives. In some instances, the amount of reflected radiant energy is sufficiently great so that the presence of microwave energy absorbing additives can be avoided altogether.

Any technique known in the art can be used to provide the interior surfaces of the microwave cavity walls with the desired level of reflective characteristics. As one approach, for example, the interior surfaces of electrically conductive cavity walls formed from aluminum, stainless-steel, copper, or the like, can be polished in order to enhance the reflective characteristics of such surfaces. As an alternative approach, instead of polishing the interior surfaces of the walls,

the interior surfaces can be coated with an intrinsically reflective material such as gold, silver, nickel, or the like.

Determining whether a surface treatment is desired for enhanced reflectivity will depend, in part, upon the type of material from which microwave cavity 16 is formed. Materials intrinsically characterized by low wall losses within the intended operating regime may not require any kind of surface treatment to enhance reflectivity. On the other hand, a surface treatment may be more desirable for materials having relatively high wall losses in the intended operating regime. For example, a microwave cavity formed from aluminum provides excellent performance in high Q applications and may not require any kind of surface treatment. However, stainless steel, which is stronger than aluminum and better for cavities subjected to high internal pressures, nonetheless contributes to higher wall losses than aluminum. Therefore, a surface treatment involving polishing and/or applying a finish of nickel, gold, or platinum may be desirable for stainless steel cavities.

In the practice of the present invention, the reflective characteristics of the interior surfaces of microwave cavity 16 can be quantitatively defined in terms of emissivity. Emissivity refers to the ratio of the radiation emitted by a surface as compared to the radiation emitted by a black body at the same temperature. Materials with lower emissivity are more reflective than materials with higher resistivity. For purposes of the present invention, the interior surfaces of microwave cavity 16 preferably have an emissivity of less than 0.1, more preferably 0.05 or less.

Microwave energy for melting is supplied to microwave cavity 16 by microwave source 18 through waveguide 20. In the practice of the present invention, microwave energy refers to electromagnetic radiation characterized by a wavelength greater than radio waves but shorter than infrared radiation. Preferred microwaves are characterized by a wavelength of about 1 mm (about 300 GHz) to about 50 cm (about 0.6 GHz). More preferred microwaves have a wavelength such that the frequency of the microwaves is in the range from about 0.9 GHz to about 5 GHz, preferably about 0.915 GHz or about 2.45 GHz.

The most common factors to be considered when selecting the most practical microwave source 20 are operating frequency, power requirement, output waveform and cost. In most case size and weight are of secondary importance, but these factors should not be overlooked if space is limited or ease of maintenance is critical. With respect to operating frequency, microwave source 18 may be tunable so that microwave source 18 is capable of generating a range of microwave frequencies. Alternatively, microwave source 18 may be of a "universal" type that generates microwaves characterized by only a single frequency. Use of a "universal" type microwave source 18 is preferred because microwave sources that generate either 2.45 GHz or 0.915 GHz microwaves, respectively, are widely available at economic prices from a number of commercial sources. Microwave sources operating at 2.45 GHz are more preferred.

Microwave source 20 should have an appropriate power output such that microwave energy source 20 is capable of radiating microwave energy at a power level sufficient to achieve melting or softening, as desired, of the polymer resin(s) being processed. On the other hand, using too much power could degrade or burn the polymer resin. Proper selection of a suitable power output for the microwave energy source would depend upon a variety of factors including the particular microwave energy source 20 being used, the polymer resin being processed, and the like. Generally, however, an available power output level in the range from about 0.5 kW to about 500 kW would be suitable in the practice of the present invention. In order to provide the flexibility to process a wide variety of polymers having different melting characteristics, it is preferred that the power output level of microwave energy source 18 be controllably variable over such a wide range. As a specific example, 2.45 GHz microwave sources are most commonly available with power output ranging from 500 Watts up to 6 kW, while a few manufacturers offer units with output up to 30 kW. Units operating at 6 kW are preferred.

The output waveform from microwave source 20 is directly related to its output spectrum and is an important factor when delivering microwave power to a high Q load. Less expensive generators utilizing power supplies commonly found in household microwave ovens have a pulsed waveform

where pulse rate is equal to the power line frequency (60 Hz in the US) and an output spectral bandwidth of approximately 5 MHz. In contrast, high performance generators utilizing switch mode power supplies have extremely low ripple, or CW, waveforms and typical output spectral bandwidths of approximately 250 kHz. A useful rule of thumb is to use a microwave source having a spectral bandwidth no more than half the coupling bandwidth of the load being heated. For example, polyethylene, being characterized by a Q factor of 4000, has a coupling bandwidth (Δf) of 613 kHz when operating at 2.45 GHz. For good operational stability this requires a microwave source having an output spectral bandwidth of no more than 300 kHz. The use of any generator with a broader spectral output will result in reduced coupling efficiency and/or operational instability. Therefore, low ripple generators, which have such capabilities, are preferred.

Waveguide 20 is typically a pipelike structure that may have any suitable cross-section for carrying microwaves from microwave source 18 to microwave cavity 16. Preferred waveguides 20 have either a square, rectangular, or circular cross-section. Like the walls used to define microwave cavity 16, waveguide 20 is generally formed from an electrically conductive material such as a corrosion-resistant metal, a metal alloy, an intermetallic composition, combinations of these, and the like. Preferred waveguides comprise aluminum, stainless steel, and/or copper.

Waveguide 20 may be flexible if desirable or necessary to allow for tolerance build-ups between the respective mounting positions of the applicator and microwave generator. Flexible waveguide 20 can also be used where movement between mounting positions is required. However, flexible waveguide 20 could be subject to fatigue failure due to repeated working of its metallic structure. Caution should be exercised during the design phase to limit the amount of flexure sufficiently to prevent any portion of the metallic structure from reaching its yield point while flexing.

Almost all microwave power delivery systems require a device which is used to match the impedance of the load to that of the waveguide and thus the microwave generator. Without this the amount of microwave power coupled to

the load may be partially reduced. The most common form of this device is a waveguide stub tuner, but other types of devices such as irises are also used. Waveguide tuners are popular for their convenience in adjusting the match while microwave power is being delivered.

Tuners are available for either manual or automatic operation. Manual tuners are adjusted by turning one or more stubs, or threaded rods, into the waveguide while the operator observes a power meter which monitors the amount of microwave power reflected from the load. Tuning is accomplished when reflected power is minimized. Automatic tuners operate essentially the same way, except that the stubs are driven by motors and sophisticated electronics are used to monitor reflected power and adjust the stubs accordingly.

Selecting between manual and automatic tuners depends more on the requirements of the process than on the cost of the device. When power is being delivered to a high Q load, the tuner often requires adjustment if the power output from the generator changes, such as is often required for regulating processes. As the generator changes output power, its center frequency also changes by as much as 30 MHz from zero to full output (this is a characteristic of all microwave generators which utilize magnetrons). When the Q of the load is 4000 and coupling bandwidth only 600 kHz, a small change in power output can result in complete loss of coupling to the load. Similarly, a dynamic process during which the characteristic impedance is constantly changing or changes gradually over time requires constant tuner adjustments in order to maintain coupling throughout the process. Under these conditions, automatic tuners are often preferred over manual tuners for their convenience and ease of use.

Most commercially available tuners, whether manual or automatic, have three or four stubs for more versatile impedance matching. In certain cases it may be possible to accomplish all of the tuning requirements using only a single stub. If this is the case, a significant amount of cost can be reduced for this components requirement. However, the ability to use only a single stub can only be determined experimentally on the actual configuration of equipment for which it is desired.

Another component typically used by most industrial microwave heating systems is a waveguide isolator which is used to protect the magnetron (the device which actually produces the microwave energy) from reflected power. The isolator includes a waveguide circulator, which directs the reflected power away from the magnetron and a dummy load which absorbs and dissipates the reflected power. Often these two elements exist as separate components which work together, but they are also available from some manufacturers incorporated together as a single component.

A means to measure reflected power for tuning purposes is also desirable. Waveguide power couplers and meters are available as separate components which can be incorporated into the heating system, but they are also available as a feature of the isolator.

Other miscellaneous waveguide components may also be desirable depending on the configuration of the equipment onto which they are to be installed. These components typically include short sections of rigid waveguide with one or more elbows to direct the microwave energy around corners. Almost any configuration is possible.

Figs. 2-5 show a specific configuration of one preferred embodiment of a polymer processing apparatus 30 of the present invention. Apparatus 30 is provided with four main components including hopper 36, main processing unit 38, transfer cylinder 40, and injection mechanism 42. Although the apparatus 30 of Figs. 2-5 is shown as having only one each of these four components, one or more additional hoppers, main processing units, transfer cylinders, and/or injection mechanisms may also be provided in order to increase the output capacity of apparatus 20.

Main processing unit 38 is cylindrically shaped and is used to melt a charge comprising a polymer resin received from raw material supply 32 provided in hopper 36. Main processing unit 38 includes a top housing section 44, center plate section 46, and bottom housing section 48. Center plate section 46 is rotatable about axis of rotation 49 and thus provides main processing unit 38 with a rotatable member to facilitate delivery, melting, and transport of polymer charges to

be processed. In the preferred embodiment shown in the Figures, top and bottom housing sections 44 and 48 are fixed and do not rotate. Center plate section 46 includes a top axial face 51 disposed proximal to top housing section 44 and a bottom axial face 53 disposed proximal to bottom housing section 48. The top axial face 51 of center plate section 46 is provided with first, second, and third cavities 50, 52, and 54 which are adapted to hold respective charges of polymer resin to be processed.

Hopper 36 and transfer cylinder 40 are disposed on the top surface 47 of top housing section 44 approximately 120 degrees apart. Intermediately between hopper 36 and transfer cylinder 40, main processing unit 38 is provided with a microwave energy source. As shown in Fig. 1, at least a portion 21 of the microwave energy source is disposed in top housing section 24. The microwave energy source is capable of directing microwave energy at the contents of one of cavities 50, 52, or 54 when center plate section 46 is rotated to a position such that one of such cavities is disposed below the microwave energy source portion 41.

Although apparatus 30 is configured with the microwave energy source portion 41 being disposed in top housing section 44, other configurations could also be used. For example, rather than being disposed in top housing section 44, the microwave energy portion 41 could be disposed in an analogous position in bottom housing section 48. Alternatively, portions of the microwave energy source could be disposed in both the top and bottom housing sections 44 and 48 in a manner such that the two portions would cooperate to irradiate the contents of an interposed cavity with microwave energy. In still other embodiments, at least a portion of the microwave energy source could be disposed in center plate section peripherally around each of the cavities. As still another alternative, the microwave source could be completely external to apparatus 30, but operationally coupled to apparatus 30 by a suitable waveguide.

It can be appreciated, therefore, that rotation of center plate section 46 about axis of rotation 49 causes each of cavities 50, 52, and 54 to move sequentially through successive delivery, irradiating, and transport positions of a polymer processing cycle. This processing cycle is successively repeated by each

cavity 50, 52, and 54 as center plate section 46 rotates. As seen best in Fig. 4, the delivery position of the cycle corresponds to the position of a cavity 50 which is rotated to a position at which a charge from supply 32 can be delivered to the cavity 50. In the embodiment shown in Fig. 4, cavity 50 disposed directly below hopper 34 is in the delivery position. To facilitate delivery, top housing section 44 is provided with a through aperture 55 allowing communication between hopper 36 and the cavity 50 in the delivery position. Preferably, controlling means (not shown) is provided so that the amount and timing of charges delivered from supply 32 through the aperture 55 can be controlled by the operator. The kind of controlling means used is not critical, and any such means could be used in accordance with conventional practices.

As seen best in Fig. 3, the irradiation position corresponds to the position of a cavity 52 which is rotated to a position at which the contents of the cavity 52 can be irradiated with microwave energy by the microwave energy source portion 41. In the embodiment shown in Fig. 3, cavity 52 disposed directly below microwave energy source portion 41 is in the delivery position. When cavity 52 holding a charge comprising a polymer resin is in this position, irradiation of the charge with microwave energy causes the polymer resin to melt. Advantageously, such melting occurs extremely rapidly and much more quickly than could be achieved using conventional melting techniques.

As seen best in Fig. 5, the transport position corresponds to the position of a cavity 54 which is rotated to a position at which the action of transfer cylinder 40 can be used to transfer the contents of the cavity 54 to the injection mechanism 42. Transfer cylinder 40 is provided with housing 56 defining a cylinder bore 58. A piston 60 capable of reciprocating movement upward and downward in cylinder bore 58 is also provided. Top housing section 44 is provided with through aperture 62 coupling the internal volume of cylinder bore 58 to cavity 54 in the transport position. The cavity 54 in the transport position is fluidly coupled to the interior of injection mechanism 42 by passageway 64. Passageway is formed from through aperture 63 and conduct section 65. As a result, downward

movement of piston 60 forces a melted charge from the transport cavity through passageway 64 and into the injection mechanism 42.

Injection mechanism 42 includes housing 66 enclosing a metering chamber 67 for holding a metered amount of the molten charge. Injection mechanism 42 is further provided with a piston 68 which is capable of reciprocating movement inside housing 66 in directions along the longitudinal axis of injection mechanism 42. Piston 68 is disposed so that movement of the piston in the direction of arrow 70 forces a molten polymer 34 through output passage 72. From output passage 72, the molten polymer can be directed to a point of use such as an extrusion die (not shown) or the internal volume of a mold (not shown), wherein the mold volume has a shape corresponding to the shape of the article to be formed.

According to a preferred mode of operation, supply 32 comprising polymer resin to be processed is provided in hopper 36. During polymer processing, the center plate section 46 is rotated until each of cavities 50, 52, and 54 is at a respective one of the delivery, irradiating, and transport positions. Typically during steady state operations, the cavity at the delivery position is capable of receiving a charge comprising the polymer resin, the cavity at the irradiation position holds a charge comprising solid polymer resin which is ready to be melted, and the cavity at the transport position holds a charge of substantially melted polymer resin ready to be transported to the injection mechanism 42. Accordingly, while the center plate section 46 is at such a position, a charge comprising a substantially unmelted polymer resin is delivered to the cavity 50 in the delivery position; the charge held in the cavity 52 disposed in the irradiating position is irradiated with an amount of microwave energy sufficient to melt substantially all of the polymer resin of said charge; and at least a portion of the charge 54 held in the cavity in the transport position is transported to metering chamber 67 such that the cavity 54 is capable of receiving a successive charge comprising a polymer resin in the next step of the processing cycle. The charge in the metering chamber 62 may then be injected into a mold (not shown) comprising

an internal volume having a shape corresponding to the article to be molded, or extruded through an extrusion die, as desired.

After the charge at the transport position is transferred to the metering chamber 67, the center plate section 46 rotates until the cavities 50, 52 and 54 are advanced to the next position of the processing cycle, and the delivery, irradiation, transport, and injection steps are then repeated. The process cycle can be repeated as many times as desired.

Fig. 6 shows an alternative embodiment of a polymer processing apparatus 100 of the present invention. Apparatus 100 is adapted for continuous processing of a supply 102 comprising a polymer material to be melted and subsequently delivered to a point of use (not shown). Apparatus 100 includes melting unit 104 and transport unit 106 operationally coupled to melting unit 104 by conduit 106. Melting is accomplished in melting unit 104, and the molten polymer is then pressurized in transport mechanism 106 for transport to the point of use.

Melting unit 104 includes electrically conductive, cylindrical housing 112 formed from sidewall 114, bottom 116, top 118, and interior partition 120. Interior partition 120 divides housing 112 into a feed zone 122 and a melting zone 124. The center region of interior partition 120 is fitted with perforated plate 126 that comprises a plurality of apertures permitting feed 102 to pass from feed zone 122 into melting zone 124. Preferably, interior partition 120 and perforated plate 126 are formed from an electrically conductive material to provide electric shielding at the top of melting zone 124. As an option, a cooling jacket (not shown) may be provided on the exterior of housing 112 in order to carry away excess heat generated during melting operations.

Feed zone 122 includes rotatable feed screw 128 operationally supported in housing 112 and bushing member 130, which defines the inner diameter of the feeding section. Bushing member 130 preferably is formed from hardened steel. Bushing member 130 is fixedly attached to housing 112 by any suitable technique including welding, riveting, bonding with an adhesive, press fitting, and the like. Charge 132 of supply 102 provided in hopper 134 is gravity

fed into helical chamber 136 defined by interior surface 131 of bushing member 130, feed member threads 138, and center member 140. Rotation of feed screw 128 motivates charge 132 through perforated plate 126 and into melting zone 124. The feed rate can be controlled easily by adjusting the rotational speed of feed screw 128. Generally, faster rotation of feed screw 128 provides higher feed rates. Preferably, feed screw 128 is rotated at a rate so that a substantially continuous, steady state flow of polymer material through melting unit 104 can be maintained.

Melting zone 124 includes cylindrically shaped, single mode chamber 140 operationally coupled to microwave source 137 by waveguide 139. Although only one microwave source 137 and waveguide 139 is shown, one or more microwave sources in combination with one or more waveguides coupled to chamber 140 at one or more positions could also be used. In the preferred embodiment shown, chamber 140 not only functions as a passage for polymer material to be conveyed through melting unit 104, but cavity 140 also functions as a single mode microwave cavity. Thus, both microwaves and the polymer material are both conveyed along a path substantially aligned with the longitudinal axis of chamber 140. In preferred embodiments, at least a portion of the interior surfaces 141, 142, 145, and/or 147 of housing 112 that define chamber 140 are sufficiently reflective (e.g., characterized by an emissivity of less than 0.1, preferably 0.05) so that not only microwaves, but also some of the radiant energy generated during melting operations, are reflected back into chamber 140 in order to enhance melting performance.

Chamber 140 generally has a diameter that is determined by the distance between the interior surface 141 on one side of chamber 140 and the interior surface 142 on the other side of chamber 140. The length of chamber 140 is determined by the distance between plate 126 at the entrance to chamber 140 and plate 144 positioned at the exit from chamber 140. The diameter of chamber 140 as measured between the interior surface 141 on one side of melting zone 124 and the interior surface 142 on the other side of melting zone 124 is preferably equal to an integer multiple of the wavelength of the microwaves being used for processing. Providing chamber 140 with such a diameter helps ensure that the microwaves will

resonate inside chamber 140 to achieve uniform energy distribution and efficient melting performance. Preferably, such diameter is 2 to 5 times, and more preferably 2 to 3 times, the wavelength of the microwaves. For example, for 2.45 GHz microwaves, the diameter of chamber 140 is preferably 10.75 cm. Principles for determining suitable geometry characteristics of a microwave cavity such as chamber 140 are described, for example, in Metaxas, "Industrial Microwave Heating", Peter Peregrinus Ltd., London (1983).

The length of chamber 140 is less critical than the diameter. In fact, chamber 140 may be provided with any suitable length as desired to ensure that the polymer residence time in chamber 140 is long enough for melting to be accomplished. The preferred length of chamber 140 can be determined according to the desired electric field strength within the volume of material being heated. The field strength should be high enough to effect reasonable rates of heating but should not be so high as to result in breakdown and electric discharge (arcing) inside chamber 140. To achieve this goal, preferred electric fields are on the order of about 375 kV/m for power levels on the order of 6 kW. Given this field strength, and for an apparatus in which 2.45 GHz microwave energy is being used at a power output level of 6 kW, use of a chamber 140 having a length in the range from 20 cm to 100 cm, preferably about 40 cm to 50 cm, would be suitable for processing a wide range of different polymers. See generally Metaxas, "Industrial Microwave Heating", Peter Peregrinus Ltd., London (1983) at page 72.

In particularly preferred embodiments of the invention, microwave transparent liner 150 is provided in chamber 140. Use of microwave transparent liner 150 confines the flowing material being processed to the core region of chamber 140, where microwave energy distribution is at a maximum. Accordingly, liner 150 promotes more uniform heating, transport, and melting of such material. In the absence of liner 150, polymer material closer to sidewall 114 may have a tendency to be too cool whereas polymer material in the center of chamber 140 may be too hot. The resultant temperature gradient may tend to have an adverse impact upon flow characteristics through melting zone 124. The polymer material could also burn or otherwise degrade.

Liner 150 is provided proximal to sidewall 114, but does not line all of bottom 116. No liner is needed proximal to such portions of bottom 116, because the polymer material is typically fully melted by the time the polymer material reaches that part of chamber 140.

Liner 150 generally is formed from a microwave transparent material that not only absorbs a relatively small percentage of the microwave energy as the microwaves travel through liner 150, but also is substantially temperature resistant so that the material will not deform, melt, or otherwise degrade during melting operations. As used herein, the term "microwave transparent" means that the material has a relative complex permittivity such that less than 1%, and more preferably less than 0.01% of the microwave energy traveling through the material is absorbed when tested according to ASTM D2520-95 Complex Permittivity (Dielectric Constant) of Solid Electrical Insulating materials at Microwave Frequencies and Temperatures at 1650°C, Test Method B (1997). A wide variety of temperature resistant, microwave transparent materials suitable for forming liner 150 are known and include the so-called low loss ceramics, quartz, glass, porcelain, alumina, combinations of these, and the like.

The thickness of the walls of liner 150 will depend upon a variety of factors including the diameter of chamber 140, the material from which liner 150 is to be formed, the power output setting of microwave source 137, the frequency of the microwave radiation generated by microwave source 137, and the like. In preferred embodiments of the invention operating at 2.45 GHz and 6 kW, and in which chamber 140 has a diameter of 10.75 cm and liner 150 is formed from quartz or a low loss ceramic, forming liner 150 with a wall thickness in the range from 2.4 to 2.7 cm, preferably 2.55 to 2.65 cm, would be suitable.

The rotational speed of feed screw 128 generally determines the pressure in chamber 140. Desirably, melting occurs in chamber 140 at a relatively low pressure that is effective to develop sufficient force to transport polymer material through chamber 140. It is particularly desirable to match the flow rate of polymer material with the heating rate so that material enters chamber 140 through plate 126 at substantially the same rate that material leaves chamber 140 through

plate 144. If the force is too low, however, the residence time in chamber 140 may be too long and polymer materials being processed could burn or otherwise degrade. On the other hand, if the pressure is too high, the polymer feed rate will be too high to achieve sufficient melting. Accordingly, melting preferably is carried out in chamber 140 under a relatively low pressure in the range from about 2 kg/cm^2 to about 40 kg/cm^2, preferably 2 kg/cm^2 to 20 kg/cm^2. In the practice of the present invention, the pressure applied to material in chamber 140 may be determined as the pressure of the material at the exit port of chamber 140, i.e., at plate 144.

After melting, molten polymer is transferred from melting unit 104 to transport unit 106 through conduit 108. Transport of molten polymer between melting unit 104 and transport unit 106 may be accomplished using any suitable motivating means such as gravity, a pump, or the like. As shown in Fig. 6, melt pump 110 is used to accomplish such transport. Melt pump 110 performs at least two important functions. Firstly, melt pump 110 helps control the flow rate of molten material transferred to transport unit 106. Additionally, melt pump helps homogenize the molten material as well. Although melt pump 110 is preferred, other devices, such as a check valve, could also be used.

Transport unit 106 includes cylindrical housing 152 enclosing metering chamber 154 for holding a metered amount of molten polymer. Transport unit 106 is further provided with piston 156 which is capable of reciprocating movement inside housing 152 in directions along the longitudinal axis of transport unit 106. Piston 156 is disposed so that movement of piston 156 in the direction of arrow 158 forces molten polymer 160 through outlet passage 162 to a point of use. Because the operation of piston 156 acts in intermittent fashion once each piston cycle to force molten polymer to the point of use, transport unit 106 incorporating piston 156 is most effectively used for injection molding applications. On the other hand, if it is desired to provide molten polymer to a point of use involving an extrusion die, then a melt pump or other similar transport device can be substituted for piston 156 in order to convey a continuous supply of molten polymer to the point of use.

Because metering chamber 154 is separate from and independently pressurizable relative to chamber 140, relatively high pressures suitable for injection molding or extrusion can be developed in metering chamber 154 without affecting the performance of melting operations. For example, relatively high pressures in the range from 10 kg/cm^2 to 2000 kg/cm^2, preferably 500 kg/cm^2 to 1000 kg/cm^2, can be easily developed in metering chamber 154 while lower pressures are maintained in chamber 140.

Fig. 7 shows another embodiment of a polymer processing apparatus 200 of the present invention that is generally similar to polymer processing apparatus 100 of Fig. 6 (for example, all parts of Fig. 7 also found in Fig. 6 bear the same identification number as the corresponding parts of Fig. 6 except that the identification numbers of Fig. 7 also include the suffix "A") , except that apparatus 200 further includes core member 202 positioned in chamber 140A. Core member 202 extends from plate 126A to plate 144A and has a surface 204 defining an inner surface for guiding polymer material in annular fashion through chamber 140A. Use of core member 202 further optimizes the heating performance of apparatus 200 by confining flowing material to an annular region of chamber 140A in which the energy distribution of the resonating microwaves is most uniform. Advantageously, core member 202 is made form a microwave transparent material as defined above so that the presence of core member 202 does not interfere with melting performance at all. When chamber 140A is a TM_{020} mode cavity operating at 2.45 GHz and having an inside diameter of 10.75 cm, liner 150 is made from quartz and has a thickness in the range from about 2.4 to 2.7 cm core member 202 preferably may have a radius in the range from 1.8 to about 2 cm.

In order to be able to optimize heating performance for differing materials and processing conditions when using the embodiments of the invention shown in Figs. 6 or 7, it may be desirable that liner 150 (or 150A as the case may be) and/or core member 202 (if any) are independently removable so that different sized parts can be inserted into place in chamber 140 (or 140A) as needed. This allows heating performance to be optimized for any kind of polymer being processed. On the other hand, for manufacturing practicability, it may be desirable

to use nonremovable liner and/or core member having characteristics that generally provide good heating performance for a range of materials over a range of operating conditions.

In embodiments of the invention including a liner (such as liner 150 or 150A) and/or a core member (such as core member 202), one or both of such components can be rotatable about the axis of chamber 140 (or 140A as the case may be) to assist with material transport or mixing. If both a liner and a core member are present and rotatable, such members can be adapted for co-rotation, counter-rotation, or both, as desired.

While this invention has been described with respect to preferred embodiments, the present invention can be further modified within the spirit and scope of this disclosure. This application is therefore intended to cover any variations, uses, or adaptations of the invention using its general principles. Further, this application is intended to cover such departures from the present disclosure as come within known or customary practice in the art to which this invention pertains and which fall within the limits of the appended claims.

WHAT IS CLAIMED IS:

1. A method of using microwave energy to process a composition comprising at least one meltable polymer, comprising the steps of:

   (a) transporting a charge comprising the composition into a cavity in which the charge can be irradiated with microwave energy;

   (b) while the charge is in the cavity, irradiating the charge with microwave energy under conditions effective to melt the polymer;

   (c) transporting the melted polymer from the cavity to a metering chamber; and

   (d) transporting the melted polymer from the metering chamber to a point of use.

2. The method of claim 1, wherein the cavity is a single mode microwave cavity.

3. The method of claim 1, wherein the cavity is a single mode microwave cavity and step (a) comprises transporting the charge along a path substantially corresponding to the path along which the microwave energy propagates in the cavity.

4. The method of claim 1, wherein the cavity is a multimode microwave cavity.

5. The method of claim 1, wherein step (b) occurs while applying a first pressure to the charge within a first pressure range, step (d) occurs while applying a second pressure to the charge within a second pressure range, and wherein the second pressure is greater than the first pressure.

6. The method of claim 5, wherein the first pressure range extends from about 2 kg/cm^2 to about 20 kg/cm^2 and the second pressure range extends from about 10 kg/cm^2 to about 2000 kg/cm^2.

7. The method of claim 5, wherein the first pressure range extends from about 3 kg/cm^2 to about 10 kg/cm^2 and the second pressure range extends from about 500 kg/cm^2 to about 1000 kg/cm^2.

8. The method of claim 1, wherein steps (a) and (b) occur while transporting the charge through the cavity under substantially steady state conditions.

9. The method of claim 1, wherein a transport mechanism comprising a piston is operationally coupled to the metering chamber such that movement of the piston is capable of causing transport of the melted polymer from the metering chamber to the point of use.

10. The method of claim 1, wherein the point of use is a cavity of an injection mold positioned in fluid communication with the metering chamber.

11. The method of claim 1, wherein the point of use is an extruder die positioned in fluid communication with the metering chamber.

12. The method of claim 1, wherein the cavity is a chamber in an electrically conductive housing, and wherein a microwave transparent material is provided as a lining on at least a portion of an interior surface of the housing so that the charge transported into the chamber does not directly contact said housing portion.

13. The method of claim 12, wherein the microwave transparent material comprises a material selected from quartz, a low loss ceramic, a glass, a porcelain, and combinations thereof.

14. The method of claim 12, wherein a core member is positioned in the cavity in a manner effective to define an annularly shaped pathway for the charge to be transported through the cavity, and wherein the core member comprises a microwave transparent material.

15. The method of claim 14, wherein the microwave transparent material of the core member comprises a material selected from quartz, a low loss ceramic, a glass, a porcelain, and combinations thereof.

16. The method of claim 1, wherein the charge comprises a nonpolar polymer and a sufficient amount of a microwave energy absorbing additive such that irradiation of the charge with microwave energy causes the polymer to melt.

17. The method of claim 16, wherein the charge comprises from about 0.01 to about 20 parts by weight of the microwave energy absorbing additive based upon 100 parts by weight of the polymer resin.

18. The method of claim 1, wherein the polymer is a thermoplastic resin.

19. The method of claim 10, further comprising the steps of:

(a) conveying the melted charge from the metering chamber to the cavity of the injection mold;

(b) allowing the melted charge to substantially solidify in the cavity of the mold; and

(c) removing the solidified article from the mold.

20. An apparatus capable of using microwave energy to process a composition comprising at least one meltable polymer, said apparatus comprising:

(a) an electrically conductive housing defining a microwave processing cavity;

(b) a microwave energy source operationally coupled to the cavity such that, while a charge of the composition is in the cavity, the charge can be irradiated with microwave energy under conditions effective to melt the polymer;

(c) a chamber in fluid communication with the cavity such that the melted polymer can be transported from the cavity to the chamber; and

(d) a transport mechanism operationally coupled to the chamber in a manner such that melted polymer in the chamber can be transported to a point of use.

21. The apparatus of claim 20, wherein the microwave processing cavity is a single mode microwave cavity.

22. The apparatus of claim 20, wherein the microwave processing cavity is a single mode microwave cavity positioned in the housing such that the composition can be transported through the housing along a path substantially corresponding to the path along which the microwave energy propagates in the cavity.

23. The apparatus of claim 20, wherein the cavity is a multimode microwave cavity.

24. The apparatus of claim 20, wherein the transport mechanism comprises a piston operationally coupled with the chamber such that movement of the piston is capable of causing transport of the melted polymer from the chamber to the point of use.

25. The apparatus of claim 20, wherein the point of use is a cavity of an injection mold positioned in fluid communication with the metering chamber.

26. The apparatus of claim 20, wherein the point of use is an extruder die positioned in fluid communication with the metering chamber.

27. The apparatus of claim 20, wherein the apparatus further comprises a microwave transparent material lining at least a portion of an interior surface of the housing such that a charge transported into the microwave processing cavity does not directly contact said housing portion.

28. The apparatus of claim 27, wherein the microwave transparent material comprises a material selected from quartz, a low pass ceramic, a glass, a porcelain, and combinations thereof.

29. The apparatus of claim 20, wherein the apparatus further comprises a core member positioned in the cavity in a manner effective to define an annularly shaped pathway for the charge to be transported through the cavity, and wherein the core member comprises a microwave transparent material.

30. A process of using microwave energy to process a composition comprising at least one meltable polymer, comprising the steps of:

(a) providing a rotatable member comprising a first cavity for holding a charge comprising a polymer resin;

(b) rotating the rotatable member to a first position such that the cavity is in communication with a supply comprising the polymer;

(c) delivering a charge comprising the polymer from the supply to the cavity;

(d) after delivering the charge to the cavity, irradiating the charge with microwave energy under conditions effective to melt substantially all of the polymer, wherein said irradiating step occurs after the rotatable member is rotated away from the first position;

(e) after melting the polymer, transporting at least a portion of the melted polymer to a metering chamber; and

(f) transporting the melted polymer from the metering chamber to a point of use.

31. The process of claim 30, wherein the rotatable member is rotatable into a plurality of positions comprising a first position, a second position, and a third position, wherein delivering of the charge to the cavity occurs when the rotatable member is in the first position, irradiating of the charge in the cavity occurs when the rotatable member is in the

second position, and transporting of the charge from the cavity to the metering chamber occurs when the rotatable member is in the third position.

32. The process of claim 30, wherein the rotatable member is rotatable into a plurality of positions comprising a first position and a second position, wherein delivering of the charge to the cavity occurs when the rotatable member is in the first position, irradiating of the charge in the cavity occurs when the rotatable member is rotating from the first position to the second position, and transporting of the charge from the cavity occurs when the rotatable member is in the second position.

33. The process of claim 30, wherein the rotatable member is substantially cylindrical and has first and second axial faces, and wherein the cavity is capable of being in open communication with the first axial face of said rotatable member in order to receive the charge.

34. The process of claim 33, wherein the rotatable member is disposed in a housing comprising a top housing section disposed proximal to the first axial face of the rotatable member and a bottom housing section disposed proximal to the second axial face of the rotatable member.

35. The process of claim 30, wherein movement of a piston causes transport of the charge from the cavity to the metering chamber.

36. The process of claim 30, wherein movement of a piston causes transport of the charge from the metering chamber to the point of use.

37. A process of using microwave energy to process a composition comprising at least one meltable polymer, comprising the steps of:

(a) providing a rotatable member, wherein the rotatable member comprises first, second, and third cavities, wherein rotation of the rotatable member causes each of the cavities to move sequentially

through successive delivery, irradiating, and transport positions of a processing cycle, wherein such cycle is successively repeated by each cavity as the rotatable member rotates, and wherein the one cavity in the delivery position is capable of receiving a charge comprising the polymer, the one cavity in the irradiating position holds a charge of the composition during irradiation, and the one cavity in the transport position holds a charge comprising a substantially melted polymer resin;

(b) delivering a charge comprising a substantially unmelted polymer resin to the cavity in the delivery position;

(c) irradiating the charge held in the cavity disposed in the irradiating position with an amount of microwave energy sufficient to melt substantially all of the polymer resin of said charge;

(d) transporting at least a portion of the charge held in the cavity in the transport position to a metering chamber such that said cavity is capable of receiving an additional charge comprising a polymer resin;

(e) injecting the charge from the metering chamber into a mold comprising an internal volume having a shape corresponding to the article to be molded;

(f) rotating the rotatable member such that each of the cavities is advanced sequentially to the next corresponding position of the processing cycle; and

(g) repeating steps (b) through (f) a plurality of times.

38. An apparatus for processing a composition comprising at least one meltable polymer, comprising:

(a) a rotatable member comprising a cavity for holding a charge of the composition;

(b) a microwave energy source operationally coupled to the cavity such that the charge in the cavity can be irradiated with microwave energy under conditions effective to melt the polymer;

(c) a metering chamber capable of being in fluid communication with the cavity so that the charge can be transported from the cavity to the metering chamber; and

(d) a first transport mechanism operationally positioned in the apparatus such that the first transport mechanism is capable of transporting the charge from the metering chamber to a point of use.

39. The apparatus of claim 38, wherein the rotatable member is rotatable into a plurality of positions comprising a first position, a second position, and a third position, wherein the charge is deliverable to the cavity when the rotatable member is in the first position, the charge in the cavity is irradiatable when the rotatable member is in the second position, and the charge is transportable from the cavity to the metering chamber when the rotatable member is in the third position.

40. The apparatus of claim 38, wherein the member is rotatable into a plurality of positions comprising a first position and a second position, wherein the charge is deliverable to the cavity when the rotatable member is in the first position, the charge is irradiatable in the cavity when the rotatable member is rotating from the first position to the second position, and the charge is transportable from the cavity when the rotatable member is in the second position.

41. The apparatus of claim 38, wherein the member is rotatable and comprises first, second, and third cavities, wherein rotation of the rotatable member causes each of the cavities to move sequentially through successive delivery, irradiating, and transport positions of a processing cycle, wherein such cycle is successively repeated by each cavity as the rotatable member rotates, and wherein the one cavity in the delivery position is capable of receiving a charge comprising a polymer resin, the one cavity in the irradiating

position holds a charge during irradiation, and the one cavity in the transport position holds a charge comprising a substantially melted polymer resin.

42. The apparatus of claim 38, wherein the apparatus further comprises a second transport mechanism operationally positioned in the apparatus such that the second transport mechanism is capable of transporting at least a portion of the charge comprising the melted polymer resin from the cavity to the metering chamber.

43. The apparatus of claim 38, wherein the first transport mechanism comprises a piston operationally disposed in the first transport mechanism such that movement of the transport piston is capable of causing transport of the charge from the metering chamber to the point of use.

44. An apparatus capable of using microwave energy to process a composition comprising at least one meltable polymer, said apparatus comprising:

(a) an electrically conductive housing defining a microwave processing cavity having a length extending from a material feed port and a material exit port;

(b) a source of microwave energy operationally coupled to the cavity such that the microwave energy propagates in single mode fashion along the length of the microwave processing cavity and such that, while a charge of the composition is in the cavity, the charge can be irradiated with the microwave energy under conditions effective to melt the polymer; and

(c) a microwave transparent material lining at least a portion of an interior surface of the housing.

45. The apparatus of claim 44, wherein the housing is cylindrically shaped.

46. The apparatus of claim 44, wherein the microwave transparent material comprises a material selected from quartz, a low pass ceramic, a glass, a porcelain, and combinations thereof.

47. The apparatus of claim 45, wherein the apparatus further comprises a core member positioned in the cavity in a manner effective to define an annularly shaped pathway for the charge to be transported through the cavity, and wherein the core member comprises a microwave transparent material.

Fig.1

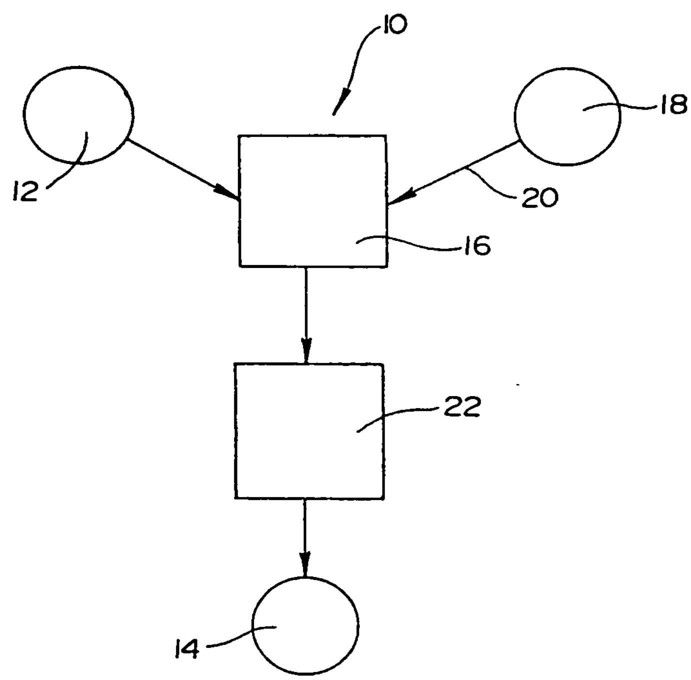

Fig.2

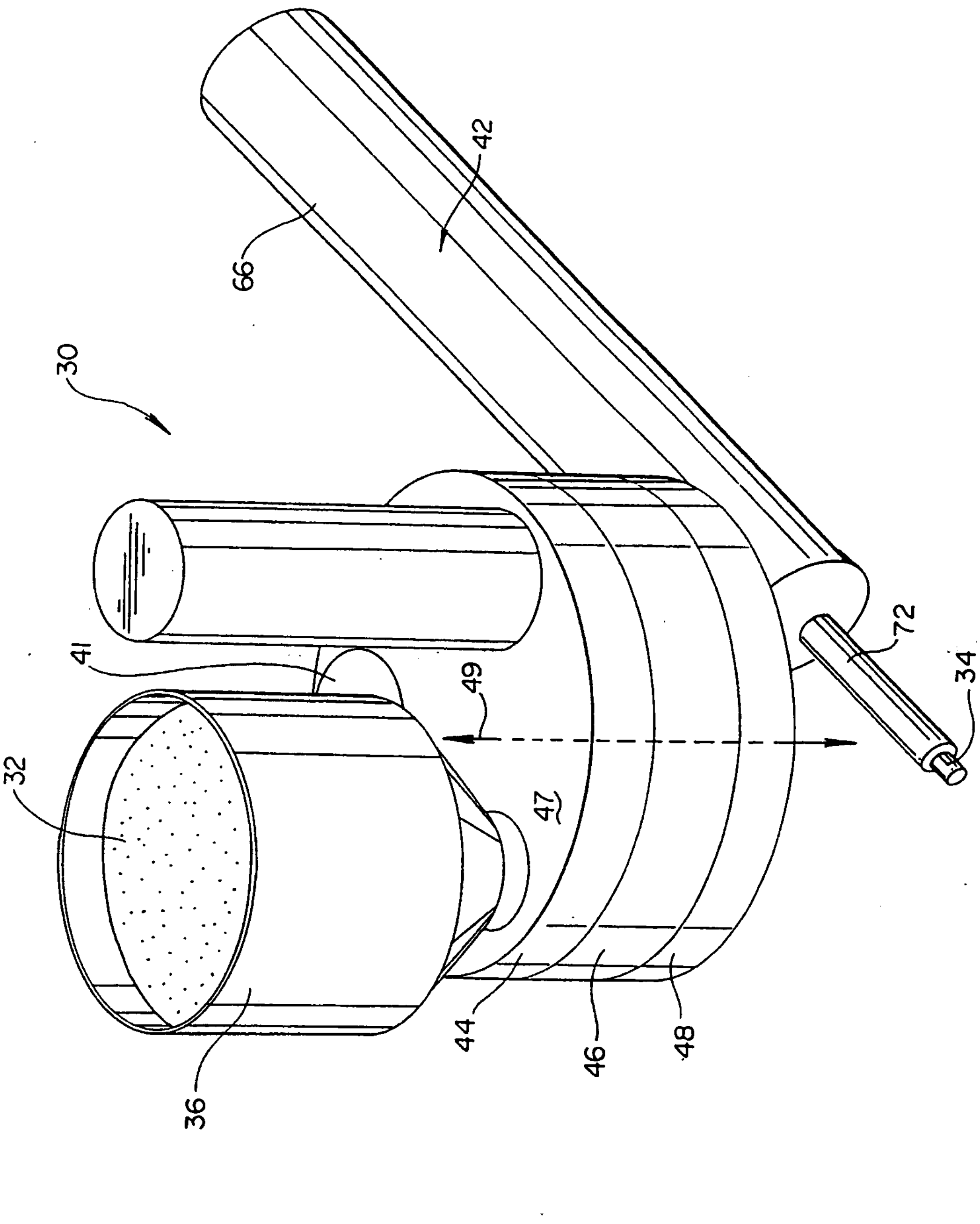

Fig.3

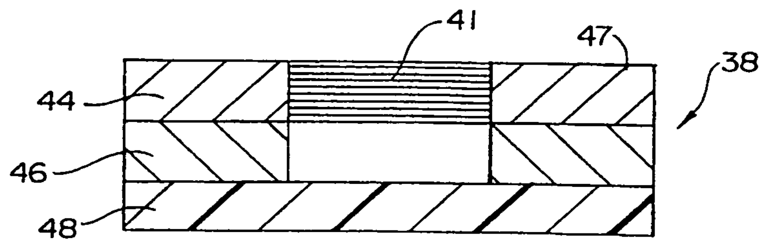

Fig.4

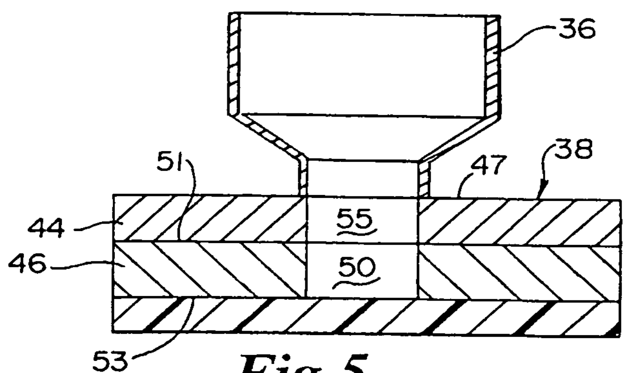

Fig.5

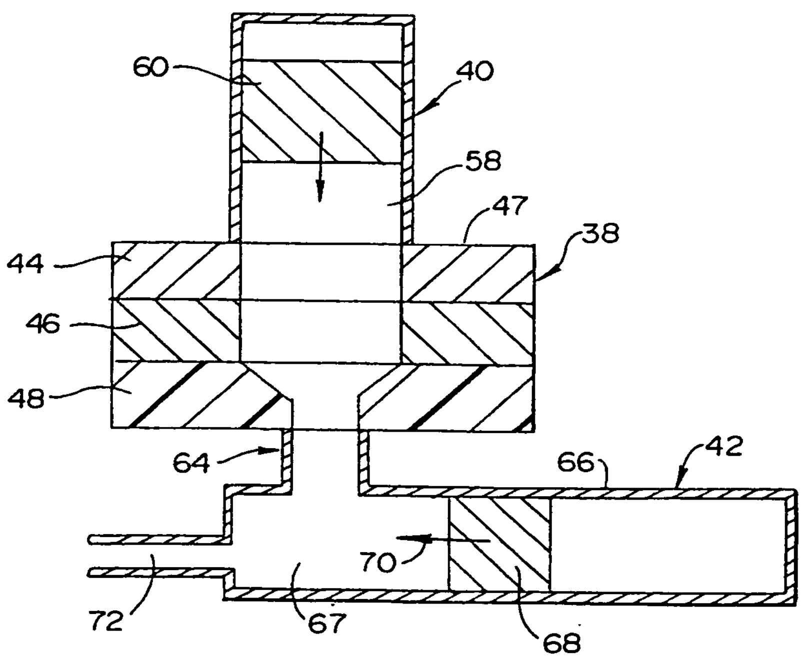

Fig. 6

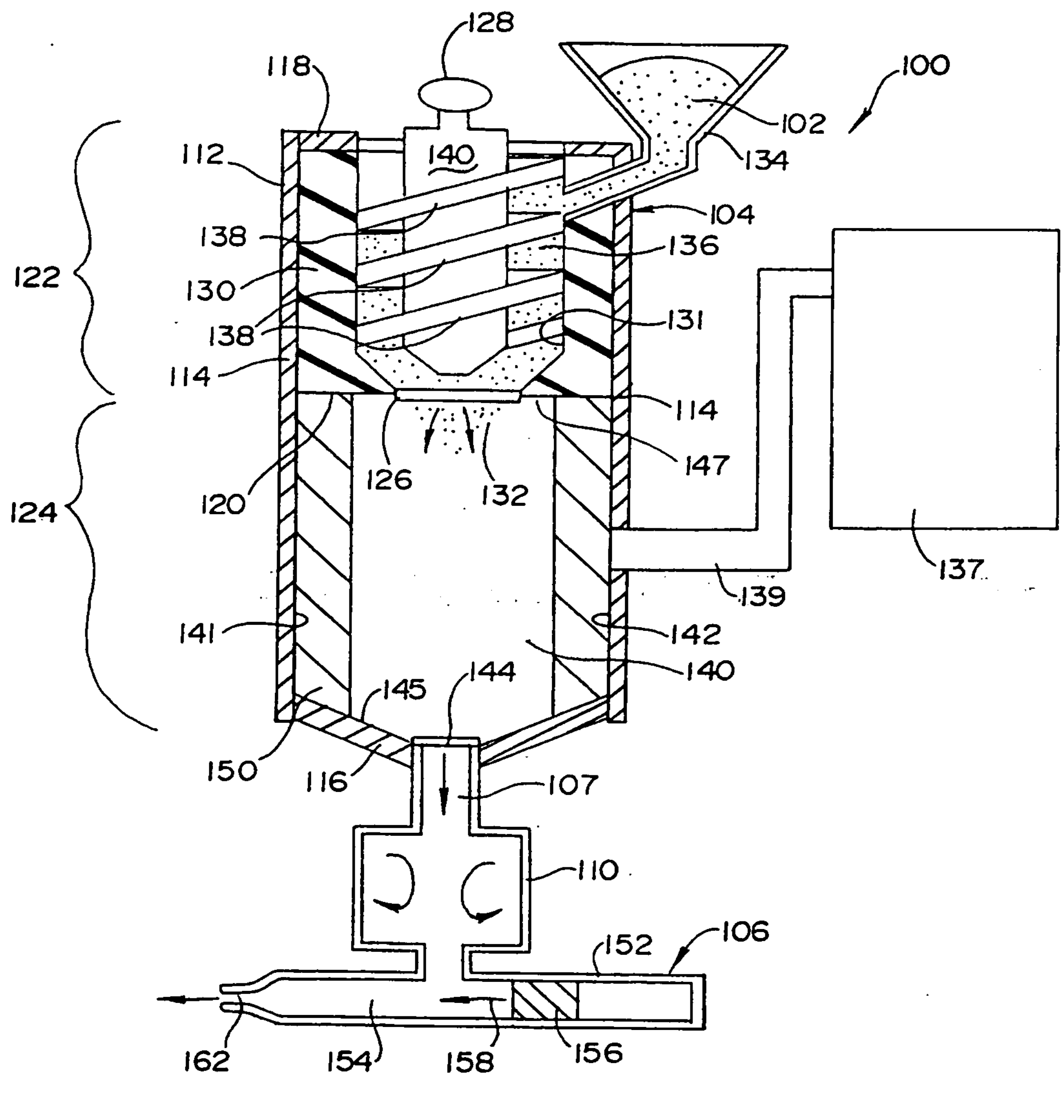
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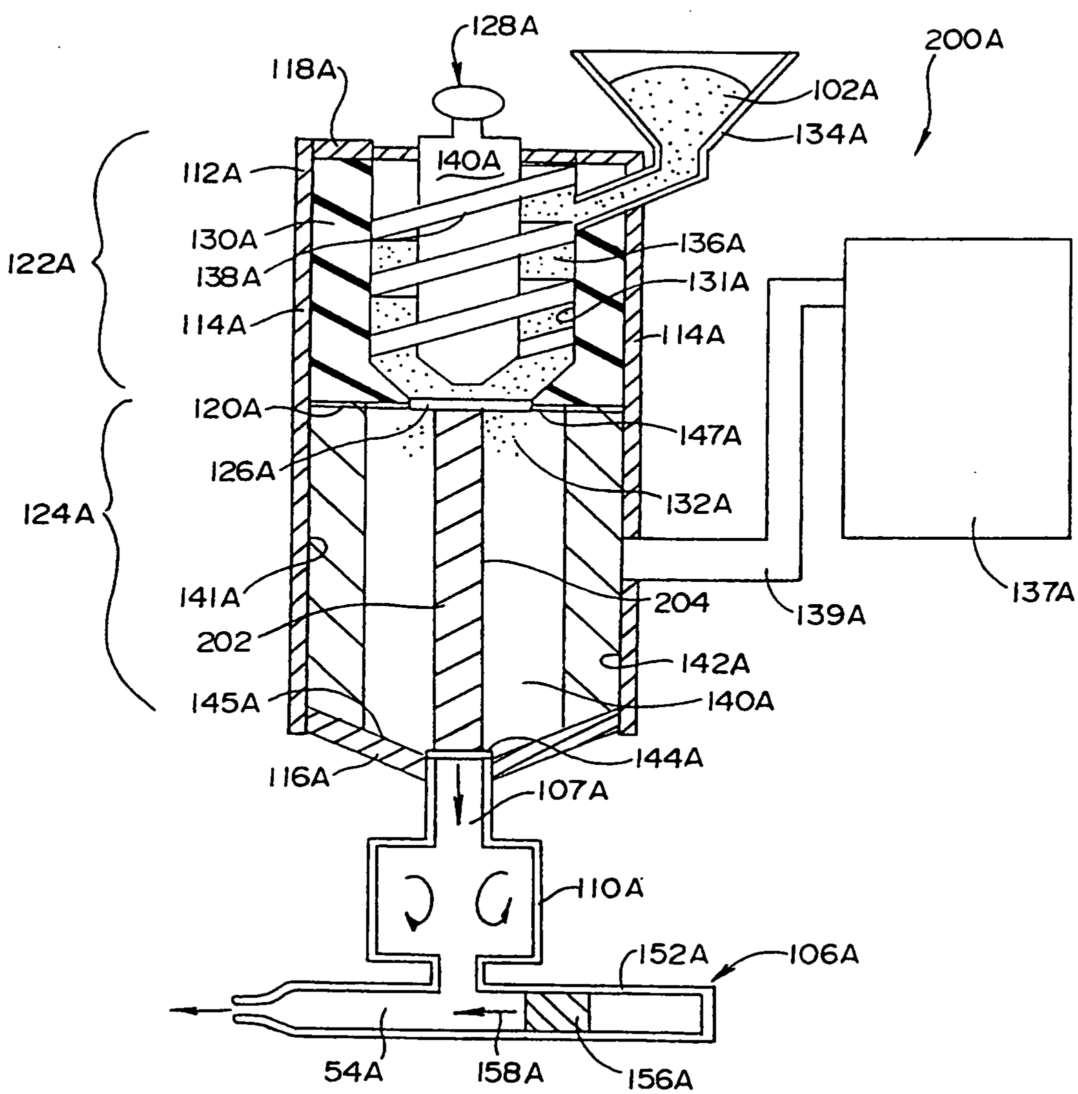
Fig. 7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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 97/17399

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 B29B13/08 B29C31/06 B29C35/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 B29B B29C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 760 228 A (KUDO MINORU) 26 July 1988 see the whole document ---	1,2, 8-13, 18-21, 24-28, 44-46
X	US 4 577 078 A (NODA YASUMASA ET AL) 18 March 1986 see column 3, line 56 - column 4, line 52; claims 1,12; figures 6,10 ---	1,2,9, 10,12, 18-21, 24,25, 27,44,45
A	US 4 003 554 A (CHAUFFOUREAUX JEAN) 18 January 1977 see the whole document ---	1-29, 44-47

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
22 January 1998	02/02/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Van Wallene, A

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INTERNATIONAL SEARCH REPORT

International Application No
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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A	DE 40 06 134 A (PILLER ANDREAS) 24 October 1991 see claims 1,2 ---	16-18
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